# Introduction to Computer Networks

## Network Layer Overview

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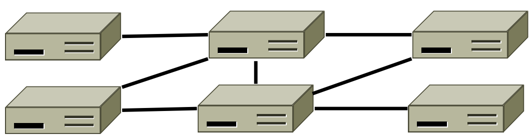
# Where we are in the Course

- Starting the Network Layer!
  - Builds on the link layer. Routers send packets over multiple networks

| |
|---|
| Application |
| Transport |
| Network |
| Link |
| Physical |

## Why do we need a Network layer?

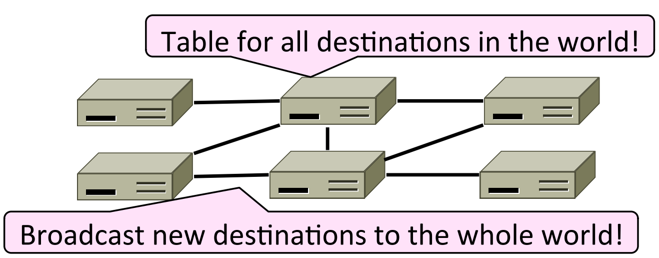
- We can already build networks with links and switches and send frames between hosts …





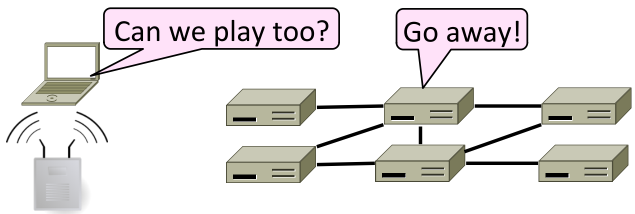
## Shortcomings of Switches

1. Don’t scale to large networks
   - Blow up of routing table, broadcast



# Shortcomings of Switches (2)

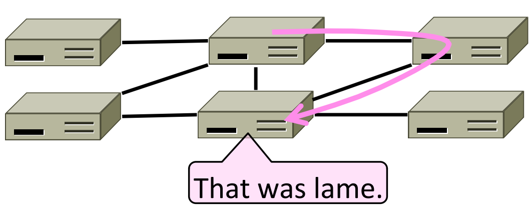
2. Don't work across more than one link layer technology
   – Hosts on Ethernet + 3G + 802.11 …






# Shortcomings of Switches (3)

3. Don't give much traffic control
   – Want to plan routes / bandwidth



# Network Layer Approach

- Scaling:
  - Hierarchy, in the form of prefixes
- Heterogeneity:
  - IP for internetworking
- Bandwidth Control:
  - Lowest-cost routing
  - Later QOS (Quality of Service)



# Topics

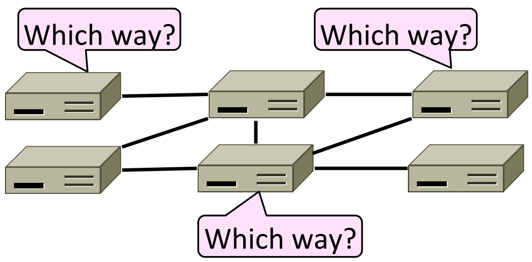
- Network service models
  - Datagrams (packets), virtual circuits
- IP (Internet Protocol)
  - Internetworking
  - Forwarding (Longest Matching Prefix)
  - Helpers: ARP and DHCP
  - Fragmentation and MTU discovery
  - Errors: ICMP (traceroute!)
- IPv6, the future of IP
- NAT, a "middlebox"
- Routing algorithms

This time

Next time

# Routing vs. Forwarding

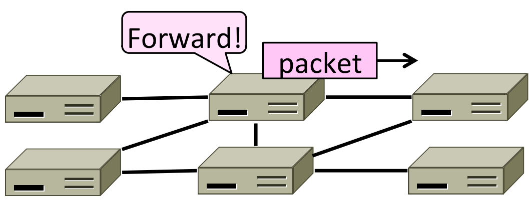
- Routing is the process of deciding in which direction to send traffic
  - Network wide (global) and expensive






# Routing vs. Forwarding (2)

- Forwarding is the process of sending a packet on its way
  - Node process (local) and fast



# Our Plan

- Forwarding this time
  - What routers do with packets
- Routing next time
  - Logically this comes first
  - But ignore it for now



# Introduction to Computer Networks

Network Services (§5.1)

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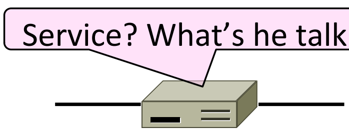
# Topic

- What kind of service does the Network layer provide to the Transport layer?
  - How is it implemented at routers?






# Two Network Service Models

- Datagrams, or connectionless service
  - Like postal letters
  - (This one is IP)

- Virtual circuits, or connection-oriented service
  - Like a telephone call

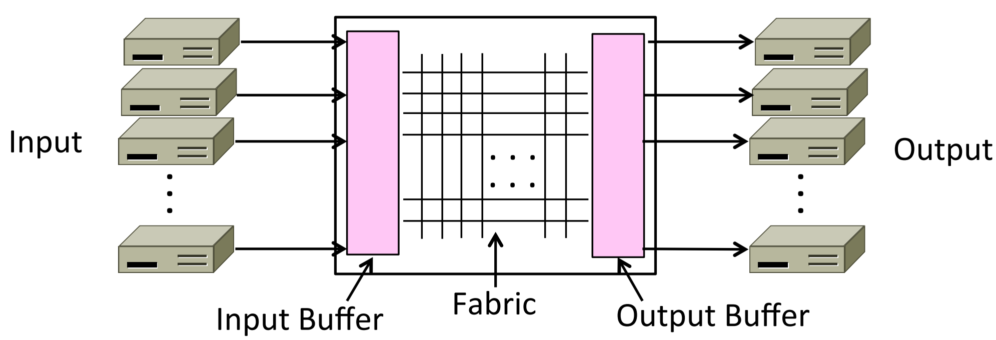
# Store-and-Forward Packet Switching

- Both models are implemented with store-and-forward packet switching
  - Routers receive a complete packet, storing it temporarily if necessary before forwarding it onwards
  - We use statistical multiplexing to share link bandwidth over time



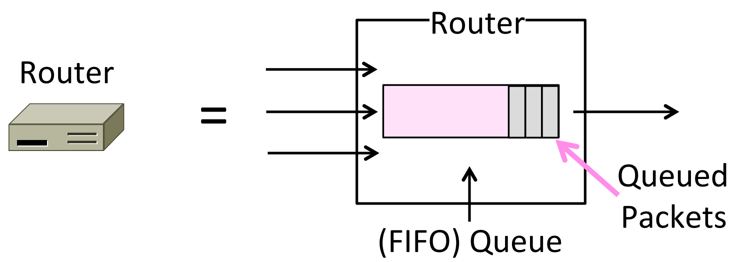
# Store-and-Forward (2)

- Switching element has internal buffering for contention



# Store-and-Forward (3)

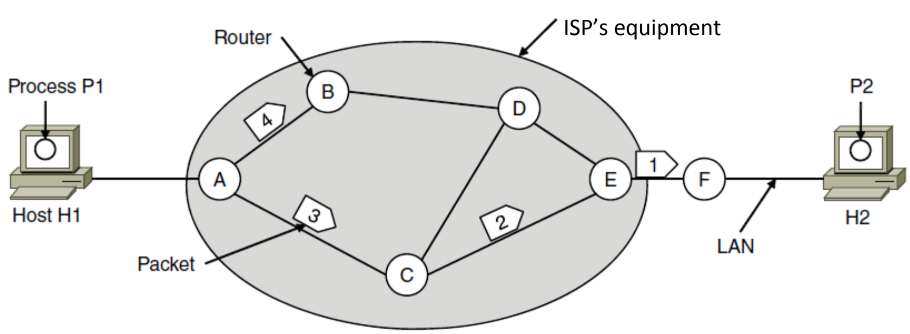
- Simplified view with per port output buffering
  - Buffer is typically a FIFO (First In First Out) queue
  - If full, packets are discarded (congestion, later)






# Datagram Model

- Packets contain a destination address; each router uses it to forward each packet, possibly on different paths



# Datagram Model (2)

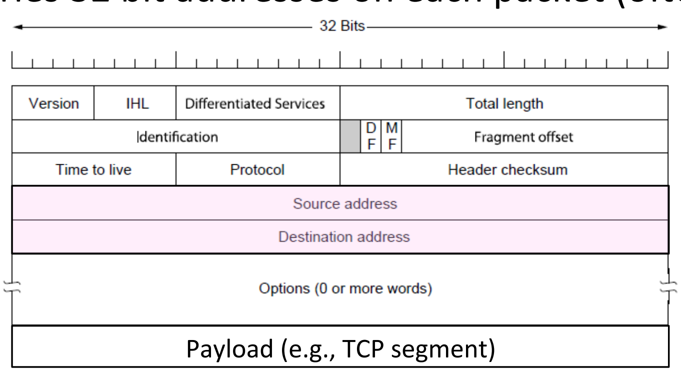
- Each router has a forwarding table keyed by address
  - Gives next hop for each destination address; may change

| A's table (initially) Dest. | A's table (initially) Line | A's table (later) | | C's Table | | E's Table | |
|---|---|---|---|---|---|---|---|
| A | | A | | A | A | A | C |
| B | B | B | B | B | A | B | D |
| C | C | C | C | C | | C | C |
| D | B | D | B | D | E | D | D |
| E | C | E | B | E | E | E | |
| F | C | F | B | F | E | F | F |



# IP (Internet Protocol)

- Network layer of the Internet, uses datagrams (next)
  - IPv4 carries 32 bit addresses on each packet (often 1.5 KB)



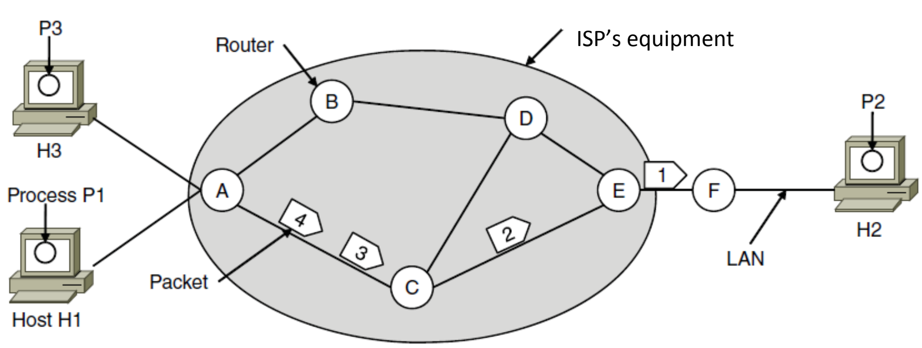
# Virtual Circuit Model

- Three phases:
  1. Connection establishment, circuit is set up
     - Path is chosen, circuit information stored in routers
  2. Data transfer, circuit is used
     - Packets are forwarded along the path
  3. Connection teardown, circuit is deleted
     - Circuit information is removed from routers
- Just like a telephone circuit, but virtual in the sense that no bandwidth need be reserved; statistical sharing of links



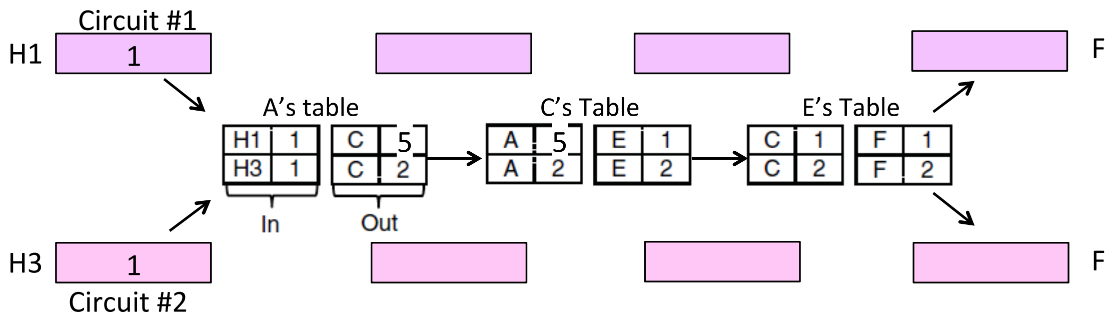
# Virtual Circuits (2)

- Packets only contain a short label to identify the circuit
  - Labels don't have any global meaning, only unique for a link



# Virtual Circuits (3)

- Each router has a forwarding table keyed by circuit
  - Gives output line and next label to place on packet

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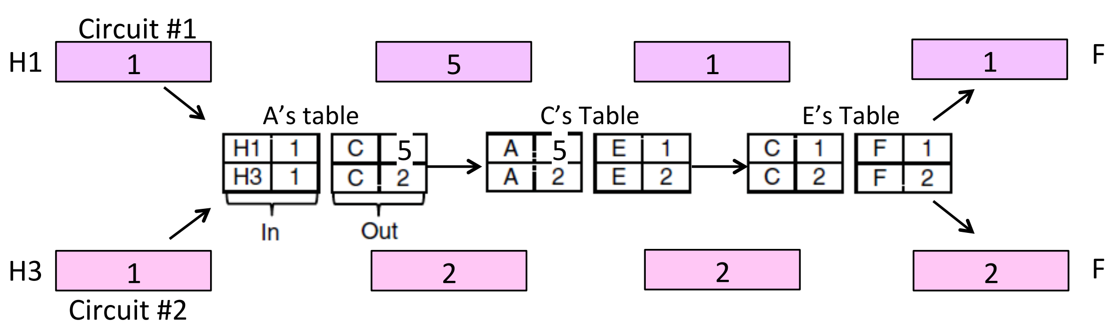
# Virtual Circuits (4)

- Each router has a forwarding table keyed by circuit
  - Gives output line and next label to place on packet

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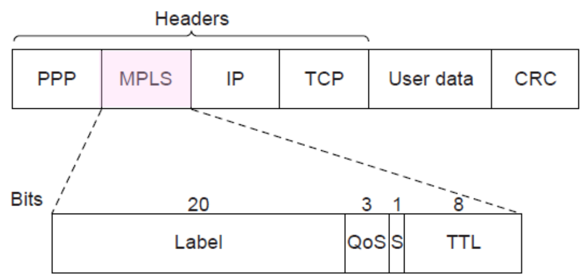
# MPLS (Multi-Protocol Label Switching, §5.6.5)

- A virtual-circuit like technology widely used by ISPs
  - ISP sets up circuits inside their backbone ahead of time
  - ISP adds MPLS label to IP packet at ingress, undoes at egress






# Datagrams vs Virtual Circuits

- Complementary strengths

| Issue | Datagrams | Virtual Circuits |
|---|---|---|
| Setup phase | Not needed | Required |
| Router state | Per destination | Per connection |
| Addresses | Packet carries full address | Packet carries short label |
| Routing | Per packet | Per circuit |
| Failures | Easier to mask | Difficult to mask |
| Quality of service | Difficult to add | Easier to add |

# Introduction to Computer Networks

Internetworking (§5.5, 5.6.1)

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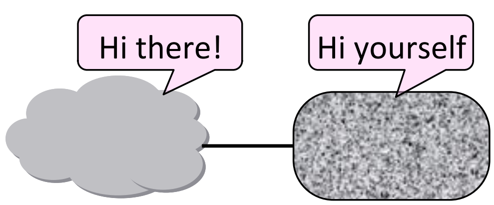
# Topic

- How do we connect different networks together?
  - This is called internetworking
  - We'll look at how IP does it



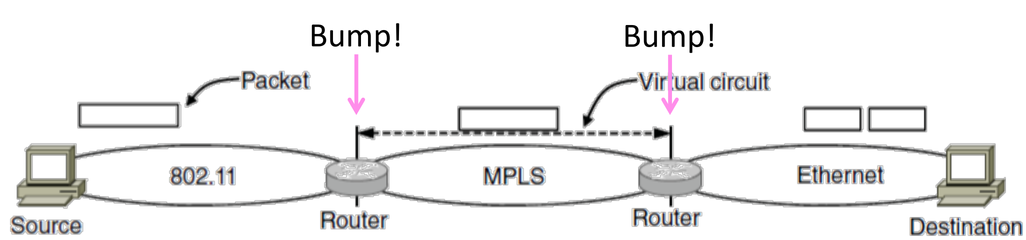
# How Networks May Differ

- Basically, in a lot of ways:
  - Service model (datagrams, VCs)
  - Addressing (what kind)
  - QOS (priorities, no priorities)
  - Packet sizes
  - Security (whether encrypted)
- Internetworking hides the differences with a common protocol. (Uh oh.)



# Connecting Datagram and VC networks

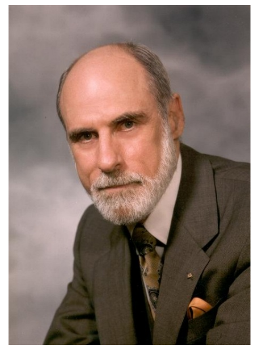
- An example to show that it's not so easy
  - Need to map destination address to a VC and vice-versa
  - A bit of a "road bump", e.g., might have to set up a VC



# Internetworking – Cerf and Kahn

- Pioneered by Cerf and Kahn, the "fathers of the Internet"
  – In 1974, later led to TCP/IP
- Tackled the problems of interconnecting networks
  – Instead of mandating a single network technology

Vint Cerf





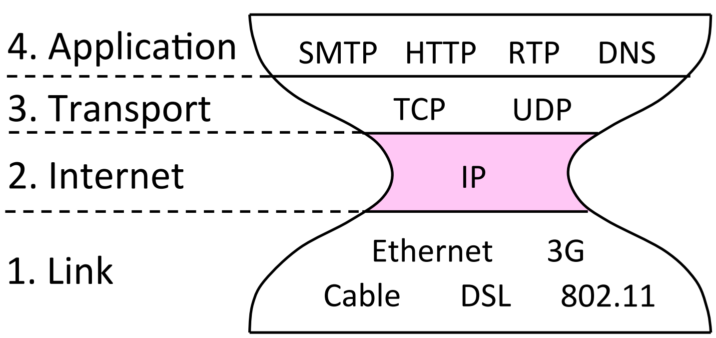
Bob Kahn





# Internet Reference Model

- IP is the "narrow waist" of the Internet
  – Supports many different links below and apps above



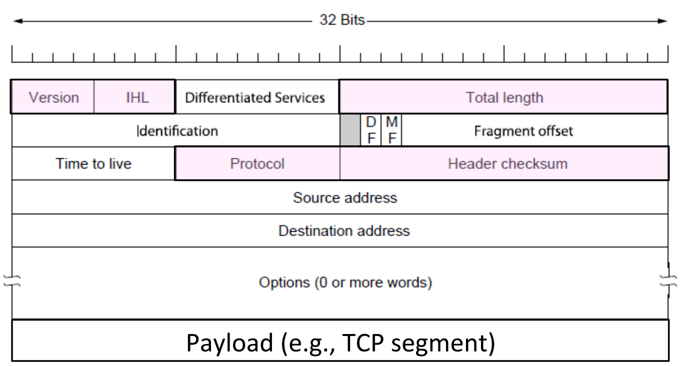
# IP as a Lowest Common Denominator

- Suppose only some networks support QOS or security etc.
  – Difficult for internetwork to support
- Pushes IP to be a “lowest common denominator” protocol
  – Asks little of lower-layer networks
  – Gives little as a higher layer service



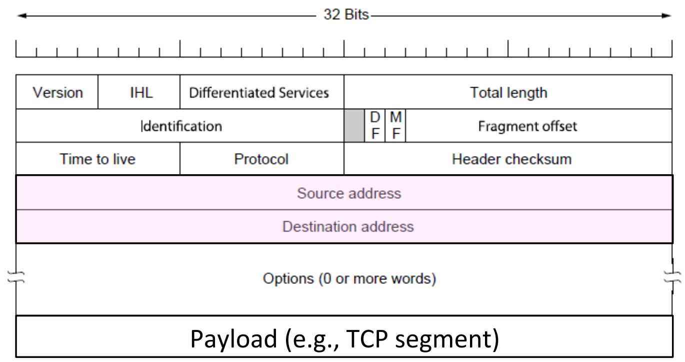
# IPv4 (Internet Protocol)

- Various fields to meet straightforward needs
  – Version, Header (IHL) and Total length, Protocol, and Header Checksum



# IPv4 (2)

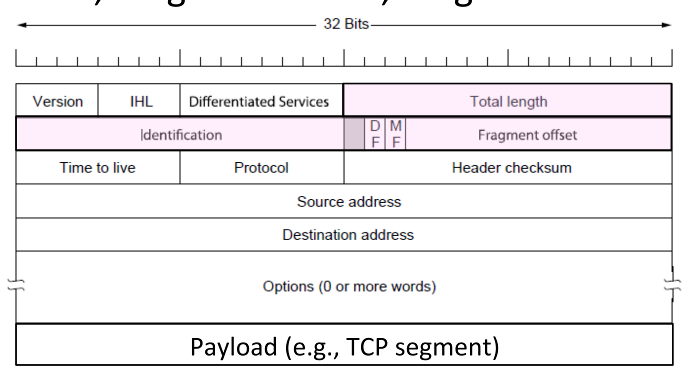
- Network layer of the Internet, uses datagrams
  - Provides a layer of addressing above link addresses (next)





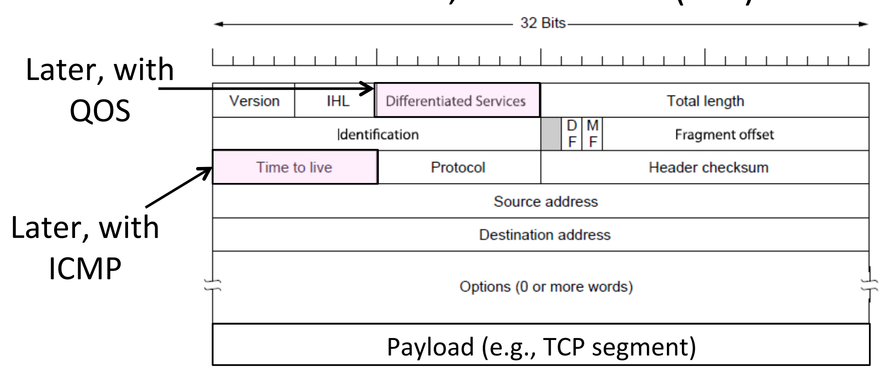

# IPv4 (3)

- Some fields to handle packet size differences (later)
  - Identification, Fragment offset, Fragment control bits



# IPv4 (4)

- Other fields to meet other needs (later, later)
  - Differentiated Services, Time to live (TTL)






# Introduction to Computer Networks

## IP Forwarding (§5.6.1-5.6.2)

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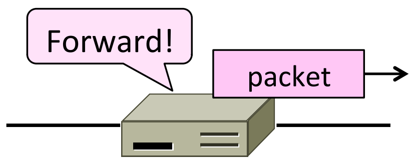
# Topic

- How do routers forward packets?
  - We'll look at how IP does it
  - (We'll cover routing later)






# Recap

- We want the network layer to:
  - Scale to large networks
    - Using addresses with hierarchy
  - Support diverse technologies
    - Internetworking with IP
  - Use link bandwidth well
    - Lowest-cost routing

This lecture

Next lecture

Next week

# IP Addresses

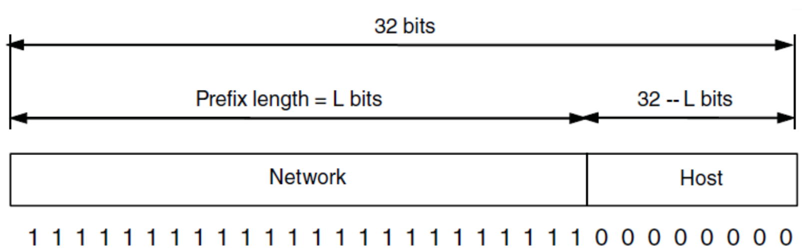
- IPv4 uses 32-bit addresses
  - Later we'll see IPv6, which uses 128-bit addresses
- Written in "dotted quad" notation
  - Four 8-bit numbers separated by dots

```
  8 bits    8 bits    8 bits    8 bits
aaaaaaaabbbbbbbbccccccccdddddddd  ↔  A.B.C.D
00010010|00011111|00000000|00000001  ↔
```



# IP Prefixes

- Addresses are allocated in blocks called <u>prefixes</u>
  - Addresses in an L-bit prefix have the same top L bits
  - There are $2^{32-L}$ addresses aligned on $2^{32-L}$ boundary



# IP Prefixes (2)

- Written in "address/length" notation
  - Address is lowest address in the prefix, length is prefix bits
  - E.g., 128.13.0.0/16 is 128.13.0.0 to 128.13.255.255
  - So a /24 ("slash 24") is 256 addresses, and a /32 is one address

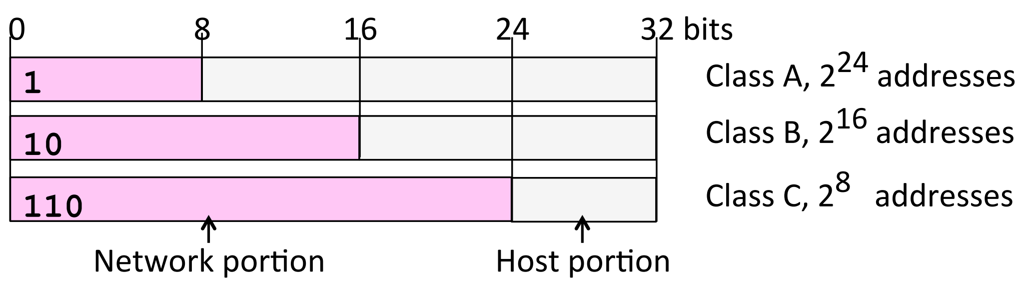
```
00010010|00011111|00000000|xxxxxxxx ↔

                                     ↔ 128.13.0.0/16
```



# Classful IP Addressing

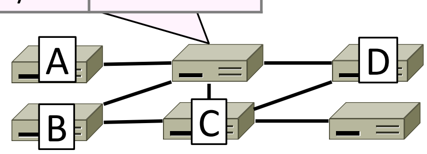
- Originally, IP addresses came in fixed size blocks with the class/size encoded in the high-order bits
  - They still do, but the classes are now ignored



# IP Forwarding

- All addresses on one network belong to the same prefix
- Node uses a table that lists the next hop for prefixes

| Prefix | Next Hop |
|---|---|
| 192.24.0.0/19 | D |
| 192.24.12.0/22 | B |






# Longest Matching Prefix

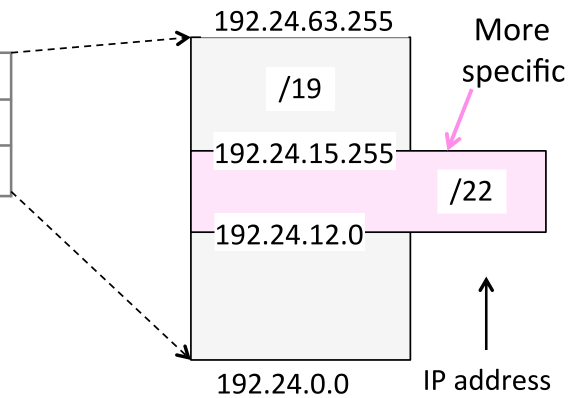
- Prefixes in the table might overlap!
  - Combines hierarchy with flexibility

- <u>Longest matching prefix</u> forwarding rule:
  - For each packet, find the longest prefix that contains the destination address, i.e., the most specific entry
  - Forward the packet to the next hop router for that prefix

# Longest Matching Prefix (2)

| Prefix | Next Hop |
|---|---|
| 192.24.0.0/19 | D |
| 192.24.12.0/22 | B |

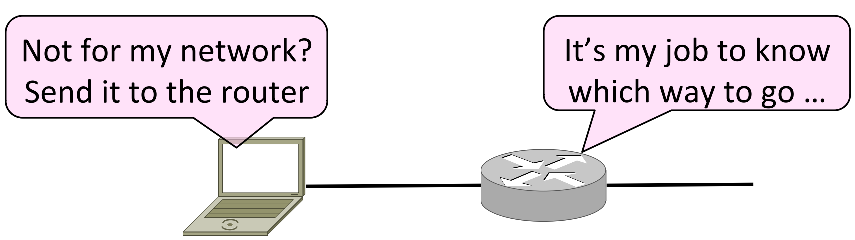
192.24.6.0 →
192.24.16.32 →






# Host/Router Distinction

- In the Internet:
  - Routers do the routing
  - Hosts send remote traffic to the nearest router



# Host Forwarding Table

- Give using longest matching prefix
  - 0.0.0.0/0 is a default route that catches all IP addresses

| Prefix | Next Hop |
|---|---|
| My network prefix | Send to that IP |
| 0.0.0.0/0 | Send to my router |



# Flexibility of Longest Matching Prefix

- Can provide default behavior, with less specifics
  - To send traffic going outside an organization to a border router
- Can special case behavior, with more specifics
  - For performance, economics, security, …

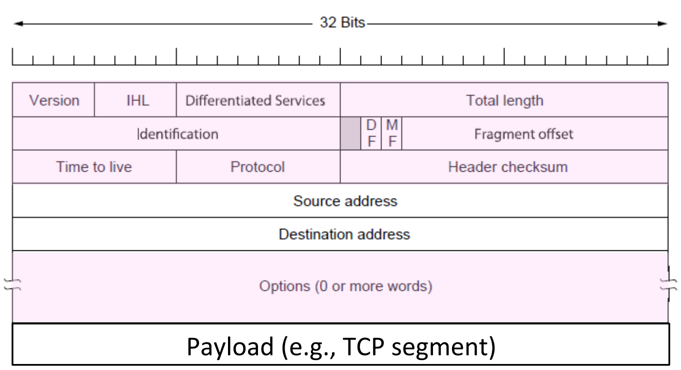
# Performance of Longest Matching Prefix

- Uses hierarchy for a compact table
  - Relies on use of large prefixes
- Lookup more complex than table
  - Used to be a concern for fast routers
  - Not an issue in practice these days



# Other Aspects of Forwarding

- It's not all about addresses …



# Other Aspects (2)

- Decrement TTL value
  - Protects against loops
- Checks header checksum
  - To add reliability
- Fragment large packets
  - Split to fit it on next link
- Send congestion signals
  - Warns hosts of congestion
- Generates error messages
  - To help mange network
- Handle various options

Coming later



# Introduction to Computer Networks

Helping IP with ARP, DHCP (§5.6.4)

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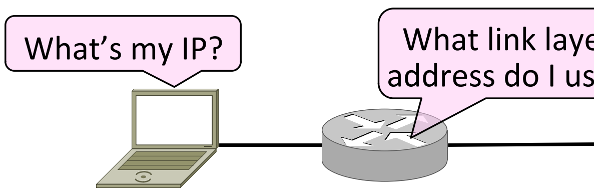
# Topic

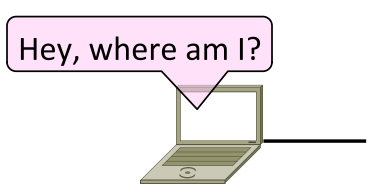
- Filling in the gaps we need to make for IP forwarding work in practice
  - Getting IP addresses (DHCP) »
  - Mapping IP to link addresses (ARP) »





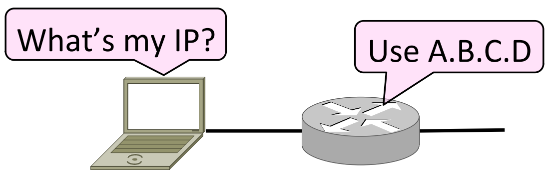

# Getting IP Addresses

- Problem:
  - A node wakes up for the first time …
  - What is its IP address? What's the IP address of its router? Etc.
  - At least Ethernet address is on NIC



# Getting IP Addresses (2)

1. Manual configuration (old days)
   – Can't be factory set, depends on use
2. A protocol for automatically configuring addresses (DHCP)
   – Shifts burden from users to IT folk






# DHCP

- DHCP (Dynamic Host Configuration Protocol), from 1993, widely used
- It leases IP address to nodes
- Provides other parameters too
  – Network prefix
  – Address of local router
  – DNS server, time server, etc.

# DHCP Protocol Stack

- DHCP is a client-server application
  - Uses UDP ports 67, 68

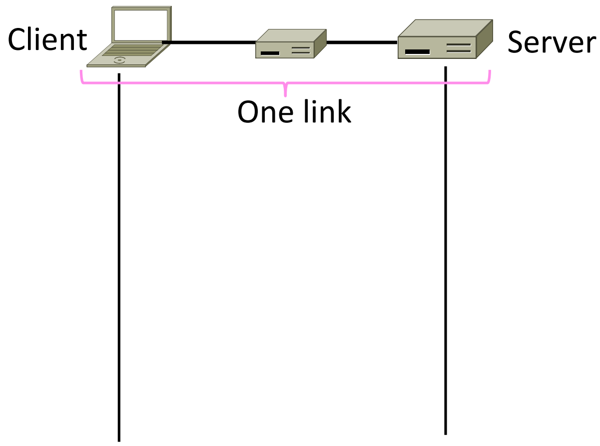
| |
|---|
| DHCP |
| UDP |
| IP |
| Ethernet |



# DHCP Addressing

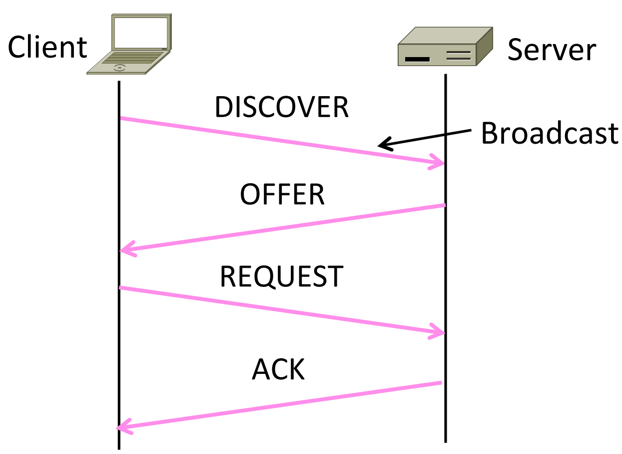
- Bootstrap issue:
  - How does node send a message to DHCP server before it is configured?
- Answer:
  - Node sends broadcast messages that delivered to all nodes on the network
  - Broadcast address is all 1s
  - IP (32 bit): 255.255.255.255
  - Ethernet (48 bit): ff:ff:ff:ff:ff:ff

# DHCP Messages






# DHCP Messages (2)



# DHCP Messages (3)

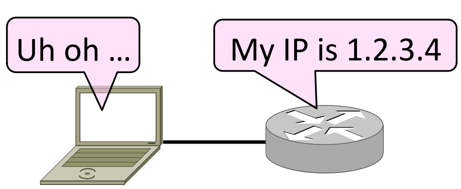
- To renew an existing lease, an abbreviated sequence is used:
  - REQUEST, followed by ACK

- Protocol also supports replicated servers for reliability



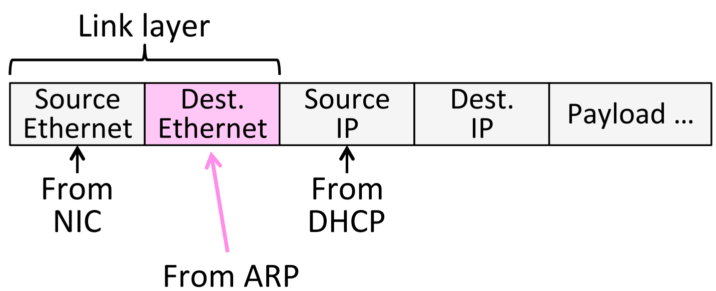
# Sending an IP Packet

- Problem:
  - A node needs Link layer addresses to send a frame over the local link
  - How does it get the destination link address from a destination IP address?



# ARP (Address Resolution Protocol)

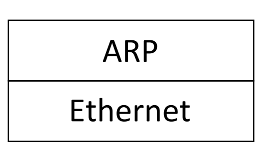
- Node uses to map a local IP address to its Link layer addresses



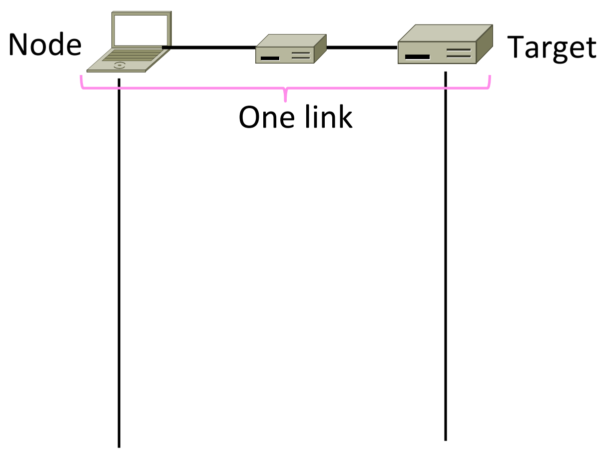



# ARP Protocol Stack

- ARP sits right on top of link layer
  - No servers, just asks node with target IP to identify itself
  - Uses broadcast to reach all nodes

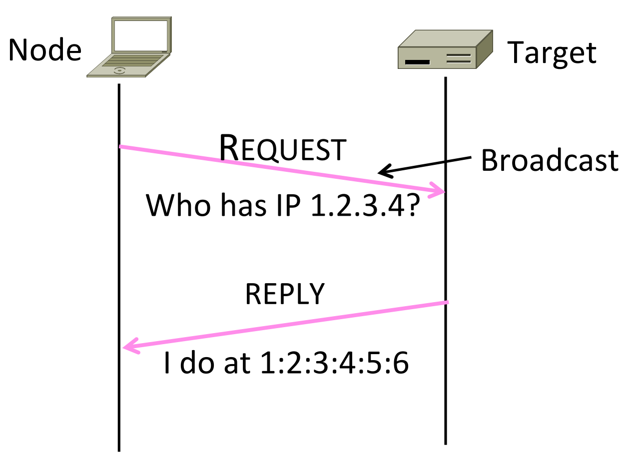


# ARP Messages






# ARP Messages (2)



# Discovery Protocols

- Help nodes find each other
  - There are more of them!
    - E.g., zeroconf, Bonjour
- Often involve broadcast
  - Since nodes aren't introduced
  - Very handy glue



# Introduction to Computer Networks

Packet Fragmentation(§5.5.5)

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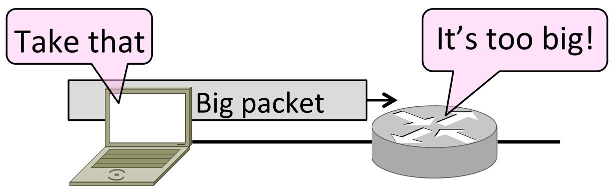
# Topic

- How do we connect networks with different maximum packet sizes?
  - Need to split up packets, or discover the largest size to use






# Packet Size Problem

- Different networks have different maximum packet sizes
  - Or MTU (Maximum Transmission Unit)
  - E.g., Ethernet 1.5K, WiFi 2.3K
- Prefer large packets for efficiency
  - But what size is too large?
  - Difficult because node does not know complete network path

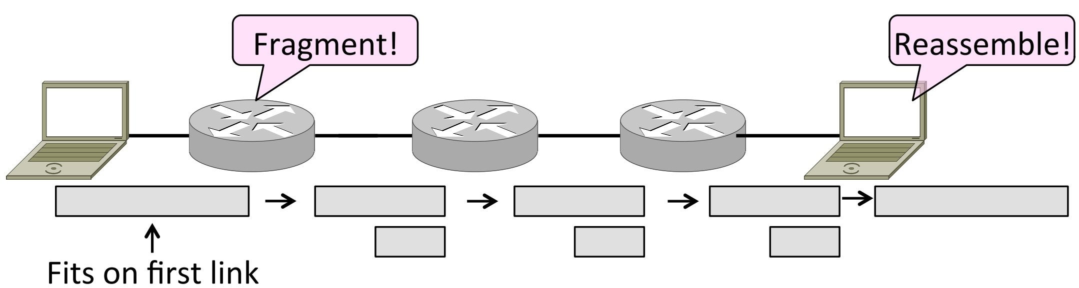
# Packet Size Solutions

- Fragmentation (now)
  - Split up large packets in the network if they are too big to send
  - Classic method, dated
- Discovery (next)
  - Find the largest packet that fits on the network path and use it
  - IP uses today instead of fragmentation



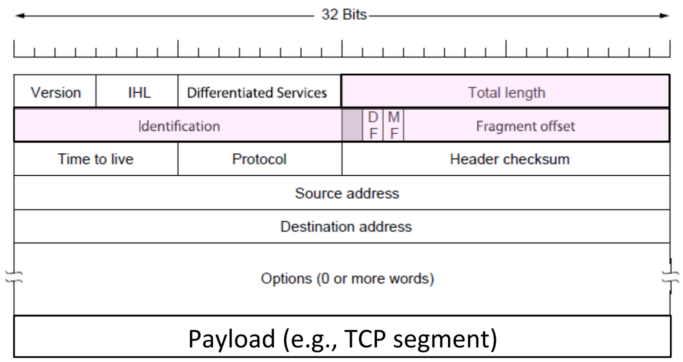
# IPv4 Fragmentation

- Routers fragment packets that are too large to forward
- Receiving host reassembles to reduce load on routers



# IPv4 Fragmentation Fields

- Header fields used to handle packet size differences
  - Identification, Fragment offset, MF/DF control bits






# IPv4 Fragmentation Procedure

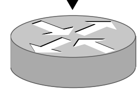
- Routers split a packet that is too large:
  - Typically break into large pieces
  - Copy IP header to pieces
  - Adjust length on pieces
  - Set offset to indicate position
  - Set MF (More Fragments) on all pieces except last
- Receiving hosts reassembles the pieces:
  - Identification field links pieces together, MF tells receiver when it has all pieces

# IPv4 Fragmentation (2)

Before
MTU = 2300

ID = 0x12ef
Data Len = 2300
Offset = 0
MF = 0

(Ignore length of headers)



After
MTU = 1500

ID =
Data Len =
Offset =
MF =

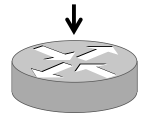
ID =
Data Len =
Offset =
MF =



# IPv4 Fragmentation (3)

Before
MTU = 2300

ID = 0x12ef
Data Len = 2300
Offset = 0
MF = 0



After
MTU = 1500

ID = 0x12ef
Data Len = 1500
Offset = 0
MF = 1

ID = 0x12ef
Data Len = 800
Offset = 1500
MF = 0

# IPv4 Fragmentation (4)

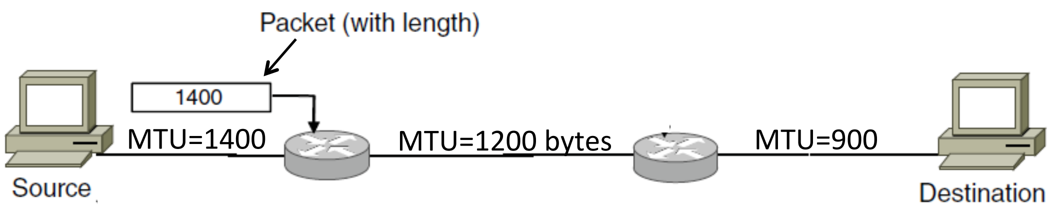
- It works!
  - Allows repeated fragmentation
- But fragmentation is undesirable
  - More work for routers, hosts
  - Tends to magnify loss rate
  - Security vulnerabilities too



# Path MTU Discovery

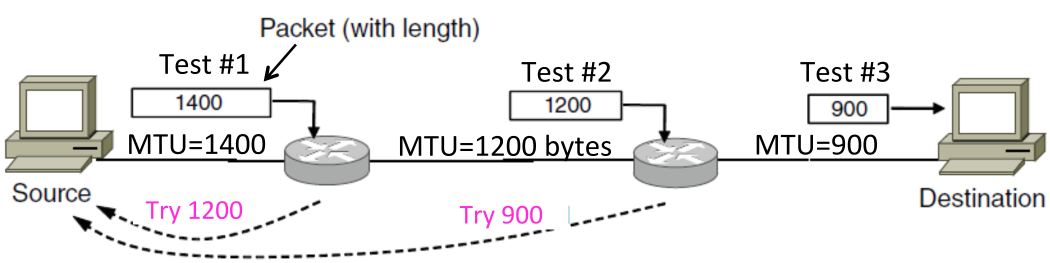
- Discover the MTU that will fit
  - So we can avoid fragmentation
  - The method in use today
- Host tests path with large packet
  - Routers provide feedback if too large; they tell host what size would have fit

# Path MTU Discovery (2)






# Path MTU Discovery (3)



# Path MTU Discovery (4)

- Process may seem involved
  - But usually quick to find right size
- Path MTU depends on the path and so can change over time
  - Search is ongoing
- Implemented with ICMP (next)
  - Set DF (Don't Fragment) bit in IP header to get feedback messages



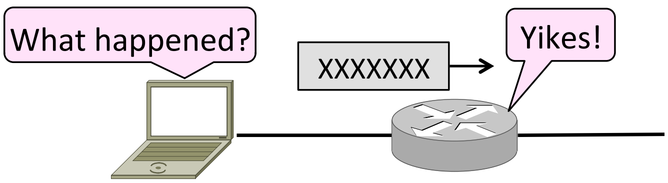
# Introduction to Computer Networks

Error Handling with ICMP (§5.6.4)

Computer Science & Engineering
UNIVERSITY *of* WASHINGTON

# Topic

- What happens when something goes wrong during forwarding?
  - Need to be able to find the problem



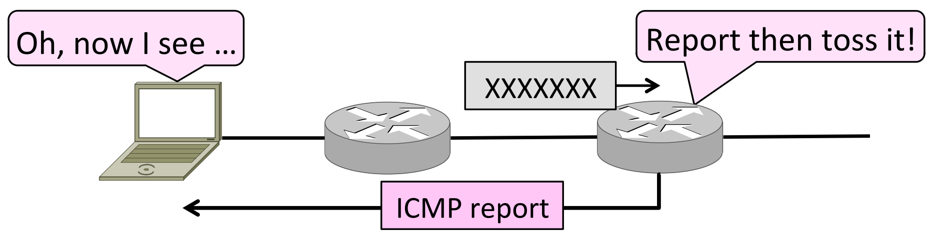



# Internet Control Message Protocol

- ICMP is a companion protocol to IP
  - They are implemented together
  - Sits on top of IP (IP Protocol=1)
- Provides error report and testing
  - Error is at router while forwarding
  - Also testing that hosts can use

# ICMP Errors

- When router encounters an error while forwarding:
  - It sends an ICMP error report back to the IP source address
  - It discards the problematic packet; host needs to rectify






# ICMP Message Format

- Each ICMP message has a Type, Code, and Checksum
- Often carry the start of the offending packet as payload
- Each message is carried in an IP packet

# ICMP Message Format (2)

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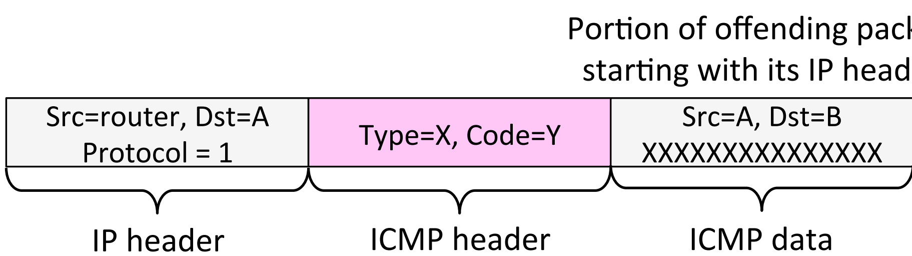





# Example ICMP Messages

| Name | Type / Code | Usage |
|---|---|---|
| Dest. Unreachable (Net or Host) | 3 / 0 or 1 | Lack of connectivity |
| Dest. Unreachable (Fragment) | 3 / 4 | Path MTU Discovery |
| Time Exceeded (Transit) | 11 / 0 | Traceroute |
| Echo Request or Reply | 8 or 0 / 0 | Ping |

Testing, not a forwarding error: Host sends Echo Request, and destination responds with an Echo Reply

# Traceroute

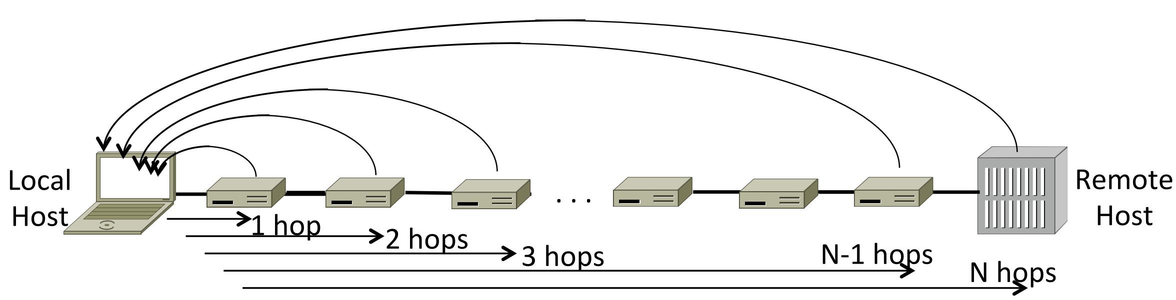
- IP header contains TTL (Time to live) field
  - Decremented every router hop, with ICMP error if it hits zero
  - Protects against forwarding loops

| | | | | | |
|---|---|---|---|---|---|
| Version | IHL | Differentiated Services | Total length | | |
| Identification | | | DF | MF | Fragment offset |
| Time to live | | Protocol | Header checksum | | |
| Source address | | | | | |
| Destination address | | | | | |
| Options (0 or more words) | | | | | |



# Traceroute (2)

- Traceroute repurposes TTL and ICMP functionality
  - Sends probe packets increasing TTL starting from 1
  - ICMP errors identify routers on the path



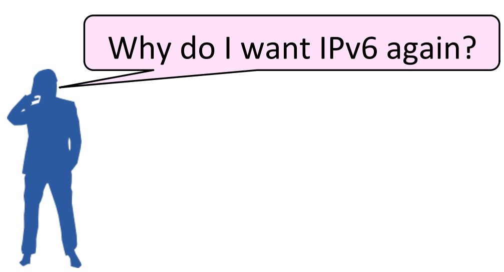
# Introduction to Computer Networks

IP Version 6 (§5.6.3)

Computer Science & Engineering
UNIVERSITY of WASHINGTON

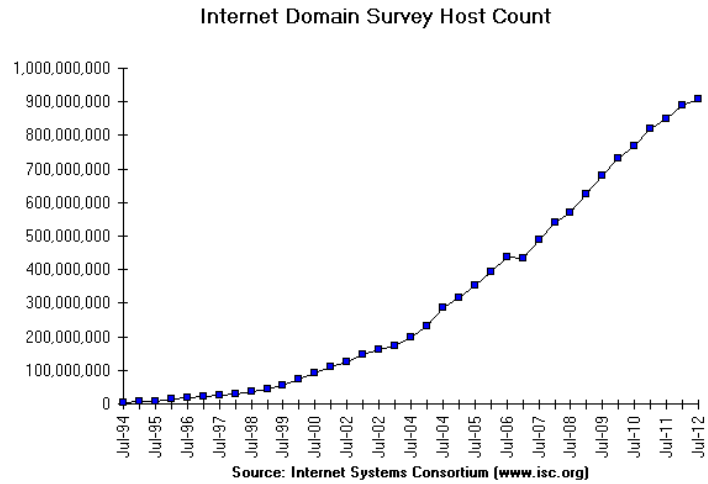
## Topic

- IP version 6, the future of IPv4 that is now (still) being deployed



# Internet Growth

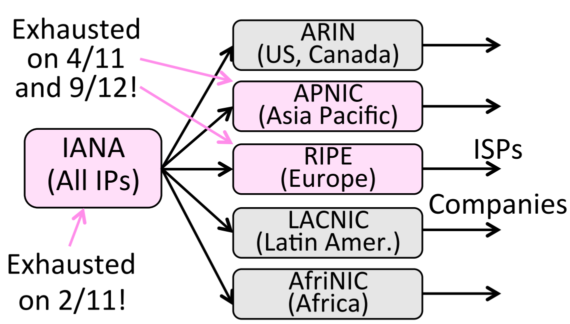
- At least a billion Internet hosts and growing …
- And we're using 32-bit addresses!






# The End of New IPv4 Addresses

- Now running on leftover blocks held by the regional registries; much tighter allocation policies




End of the world ? 12/21/12?

# IP Version 6 to the Rescue

- Effort started by the IETF in 1994
  - Much larger addresses (128 bits)
  - Many sundry improvements
- Became an IETF standard in 1998
  - Nothing much happened for a decade
  - Hampered by deployment issues, and a lack of adoption incentives
  - Big push ~2011 as exhaustion looms



# IPv6 Deployment

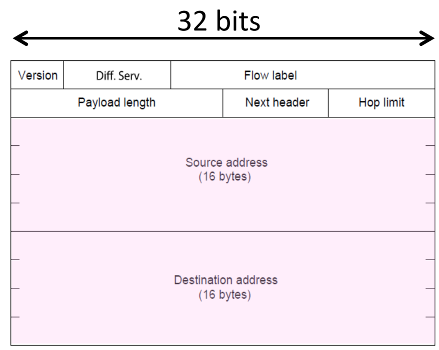
Percentage of users accessing Google via IPv6


Source: Google IPv6 Statistics, 30/1/13

Time for growth!

# IPv6

- Features large addresses
  - 128 bits, most of header
- New notation
  - 8 groups of 4 hex digits (16 bits)
  - Omit leading zeros, groups of zeros

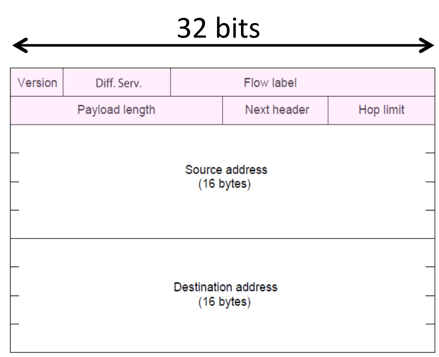



Ex: 2001:0db8:0000:0000:0000:ff00:0042:8329
→



# IPv6 (2)

- Lots of other, smaller changes
  - Streamlined header processing
  - Flow label to group of packets
  - Better fit with "advanced" features (mobility, multicasting, security)



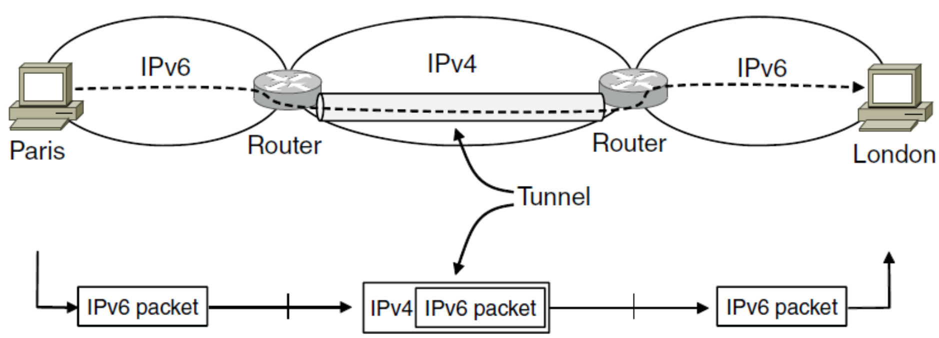
# IPv6 Transition

- The Big Problem:
  - How to deploy IPv6?
  - Fundamentally incompatible with IPv4
- Dozens of approaches proposed
  - Dual stack (speak IPv4 and IPv6)
  - Translators (convert packets)
  - Tunnels (carry IPv6 over IPv4) »



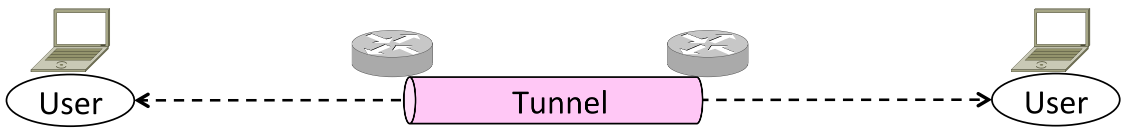
# Tunneling

- Native IPv6 islands connected via IPv4
  - Tunnel carries IPv6 packets across IPv4 network



# Tunneling (2)

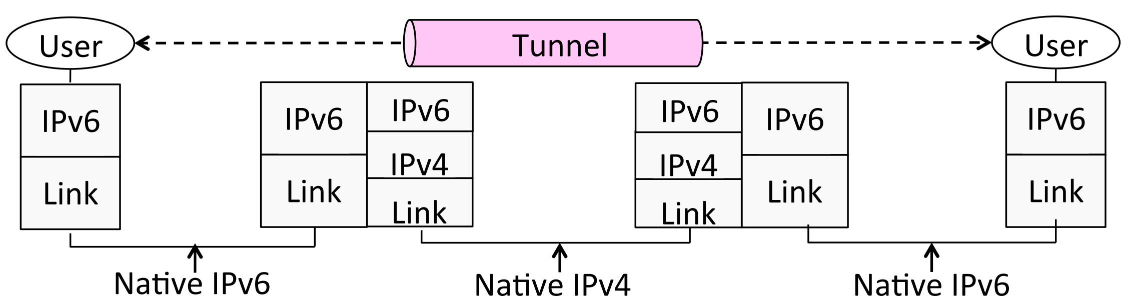
- Tunnel acts as a single link across IPv4 network






# Tunneling (3)

- Tunnel acts as a single link across IPv4 network
  - Difficulty is to set up tunnel endpoints and routing



# Introduction to Computer Networks

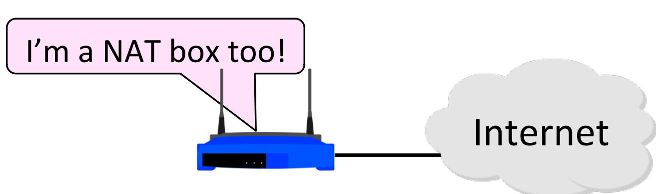
Network Address Translation (§5.6.2)

Computer Science & Engineering

UNIVERSITY of WASHINGTON

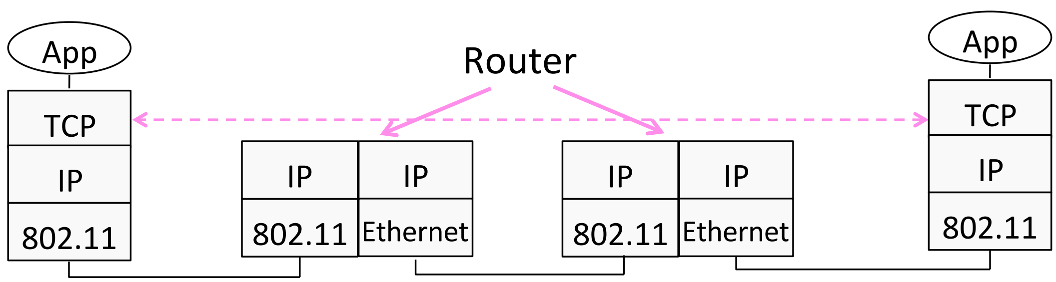
## Topic

- What is NAT (Network Address Translation)? How does it work?
  - NAT is widely used at the edges of the network, e.g., homes



# Layering Review

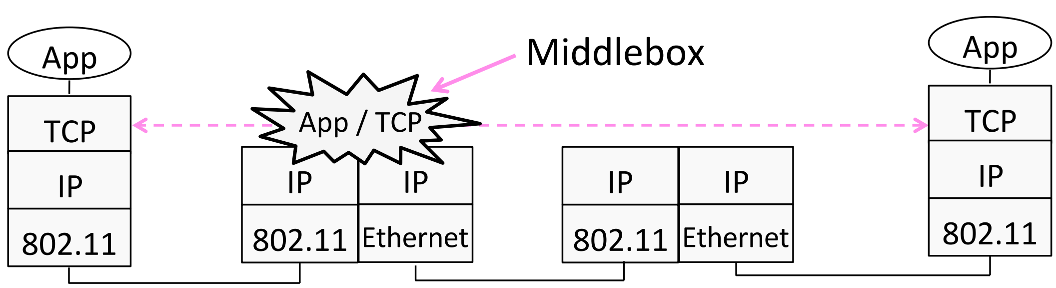
- Remember how layering is meant to work?
  - "Routers don't look beyond the IP header." Well …






# Middleboxes

- Sit "inside the network" but perform "more than IP" processing on packets to add new functionality
  - NAT box, Firewall / Intrusion Detection System



# Middleboxes (2)

- Advantages
  - A possible rapid deployment path when there is no other option
  - Control over many hosts (IT)
- Disadvantages
  - Breaking layering interferes with connectivity; strange side effects
  - Poor vantage point for many tasks

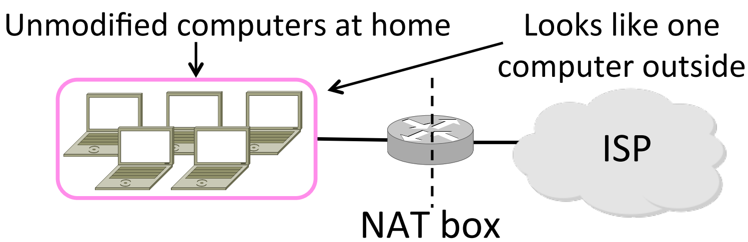


# NAT (Network Address Translation) Box

- NAT box connects an internal network to an external network
  - Many internal hosts are connected using few external addresses
  - Middlebox that "translates addresses"
- Motivated by IP address scarcity
  - Controversial at first, now accepted

# NAT (2)

- Common scenario:
  - Home computers use "private" IP addresses
  - NAT (in AP/firewall) connects home to ISP using a single external IP address






# How NAT Works

- Keeps an internal/external table
  - Typically uses IP address + TCP port
  - This is address and port translation

| What host thinks | What ISP thinks |
|---|---|
| **Internal IP:port** | **External IP : port** |
| 192.168.1.12 : 5523 | 44.25.80.3 : 1500 |
| 192.168.1.13 : 1234 | 44.25.80.3 : 1501 |
| 192.168.2.20 : 1234 | 44.25.80.3 : 1502 |

- Need ports to make mapping 1-1 since there are fewer external IPs

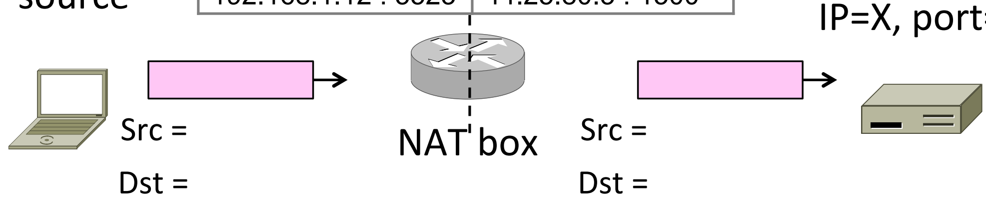
# How NAT Works (2)

- Internal → External:
  - Look up and rewrite Source IP/port

Internal source

| Internal IP:port | External IP : port |
|---|---|
| 192.168.1.12 : 5523 | 44.25.80.3 : 1500 |

External destination IP=X, port=Y





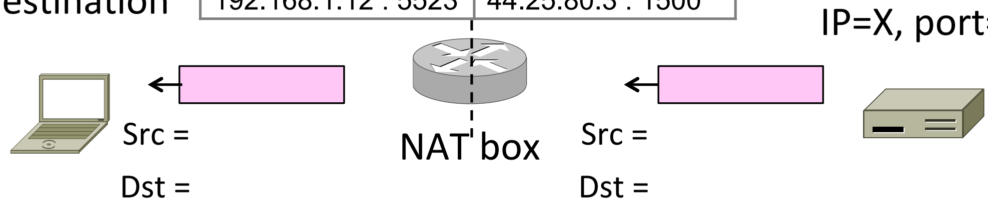

# How NAT Works (3)

- External → Internal
  - Look up and rewrite Destination IP/port

Internal destination

| Internal IP:port | External IP : port |
|---|---|
| 192.168.1.12 : 5523 | 44.25.80.3 : 1500 |

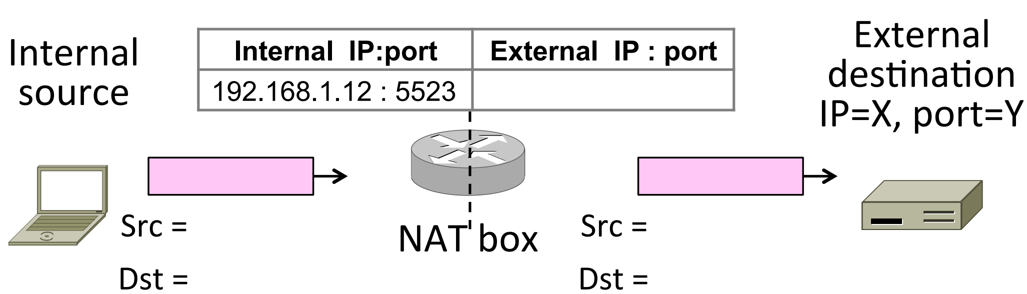
External source IP=X, port=Y



# How NAT Works (4)

- Need to enter translations in the table for it to work
  - Create external name when host makes a TCP connection

| Internal IP:port | External IP : port |
|---|---|
| 192.168.1.12 : 5523 | |






# NAT Downsides

- Connectivity has been broken!
  - Can only send incoming packets after an outgoing connection is set up
  - Difficult to run servers or peer-to-peer apps (Skype) at home
- Doesn't work so well when there are no connections (UDP apps)
- Breaks apps that unwisely expose their IP addresses (FTP)

# NAT Upsides

- Relieves much IP address pressure
  - Many home hosts behind NATs
- Easy to deploy
  - Rapidly, and by you alone
- Useful functionality
  - Firewall, helps with privacy
- Kinks will get worked out eventually
  - "NAT Traversal" for incoming traffic