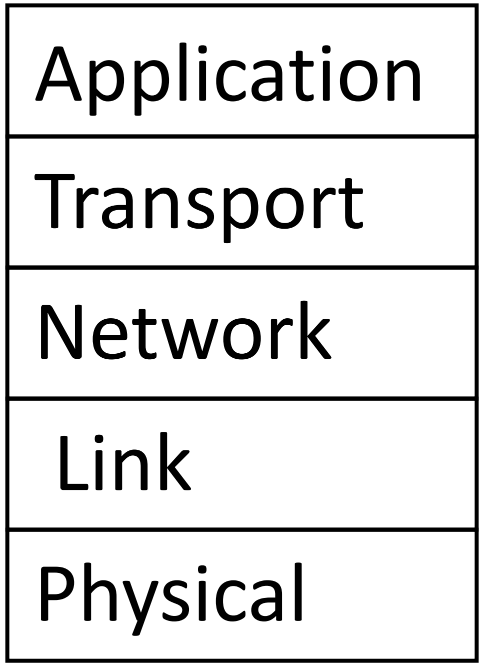
Network Layer (IP)

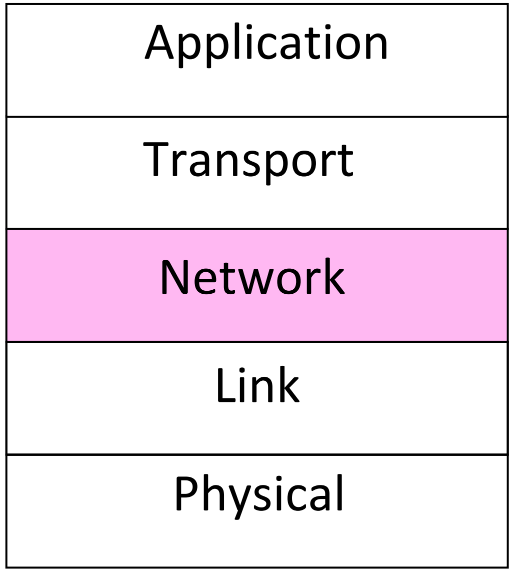
Recall the protocol stack



Application	– Programs that use network service
Transport	– Provides end-to-end data delivery
Network	– Send packets over multiple networks
Link	– Send frames over one or more links
Physical	– Send bits using signals

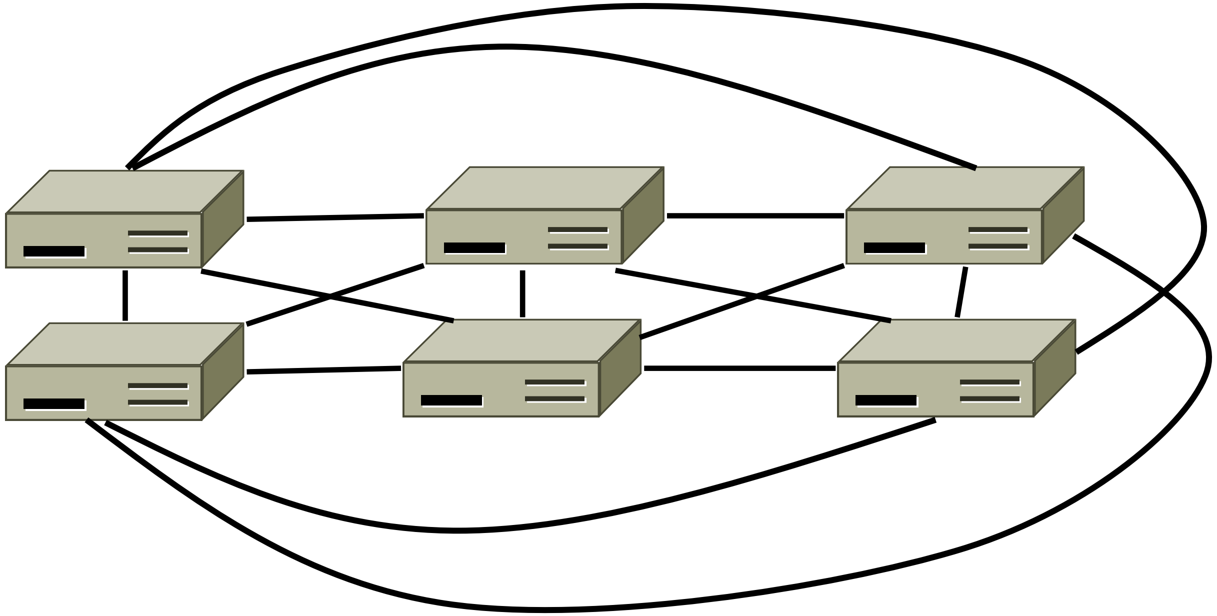
Network Layer

- How to get packets from source to destination



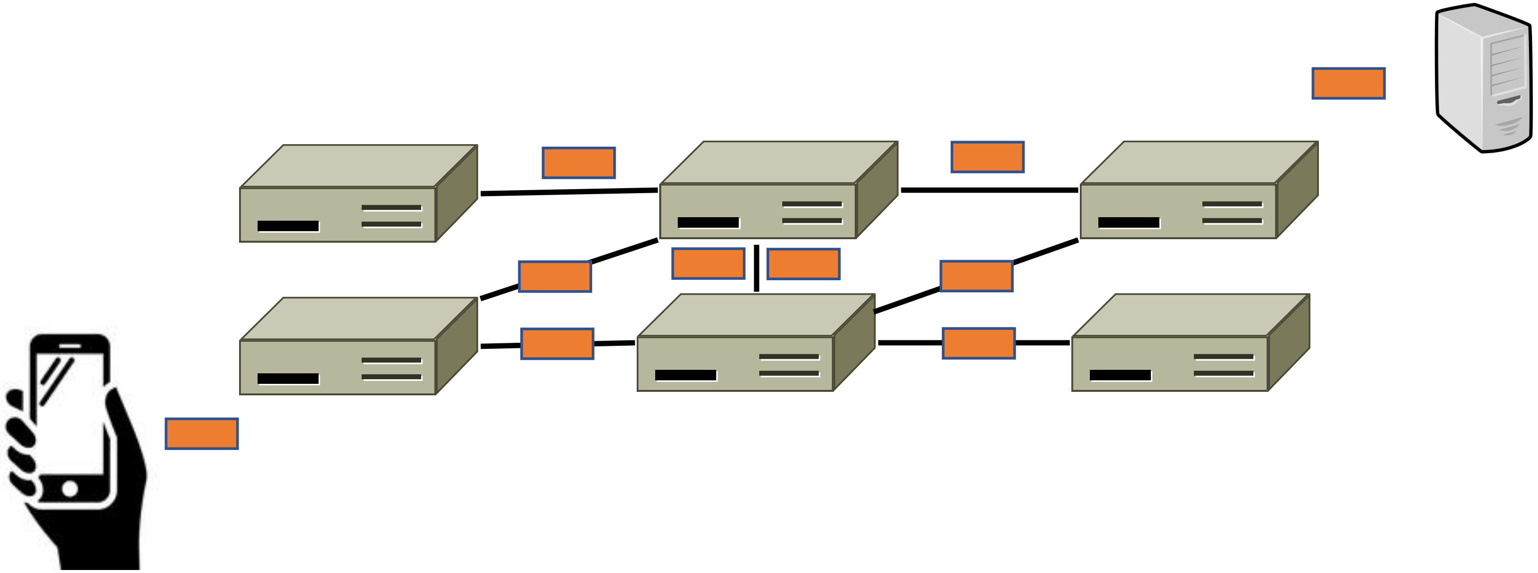
Why do we need a Network layer?

- Cannot afford to directly connect everyone
  - Cost and link layer diversity



Why do we need a Network layer? (2)

- Cannot broadcast all packets at global scale

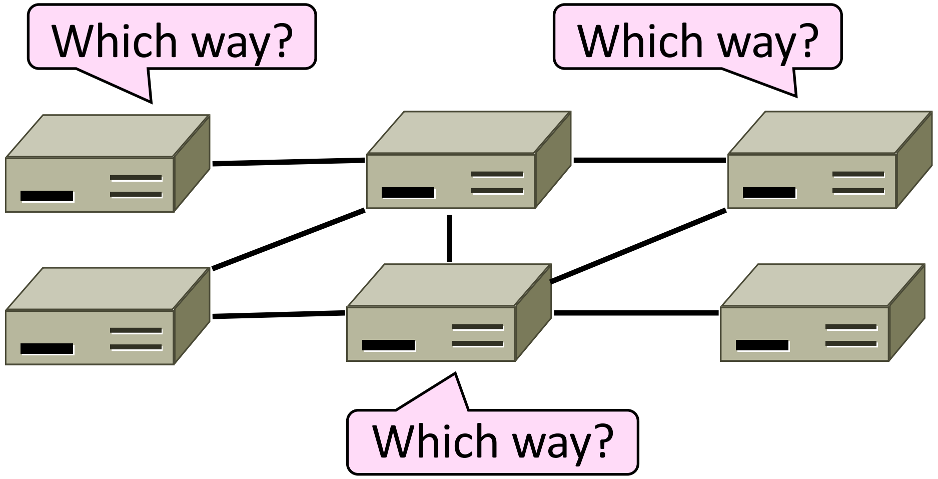


Why do we need a Network layer? (3)

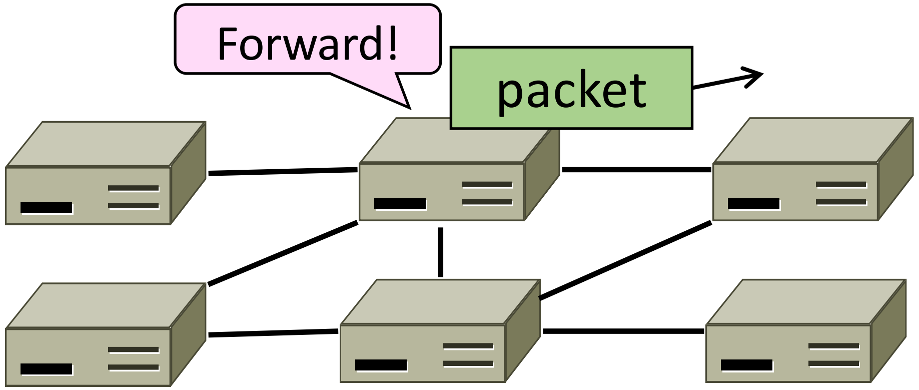
- Internetworking
  - Need to connect different link layer networks
- Addressing
  - Need a globally unique way to “address” hosts
- Routing and forwarding
  - Need to find and traverse paths between hosts

Routing versus Forwarding

- Routing: deciding the direction to send traffic



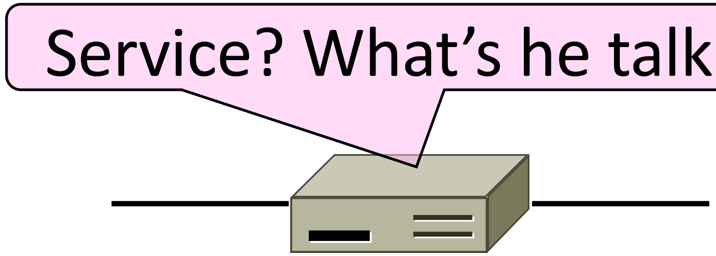
- Forwarding: sending a packet on its way



Network Service Models

Network service models

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



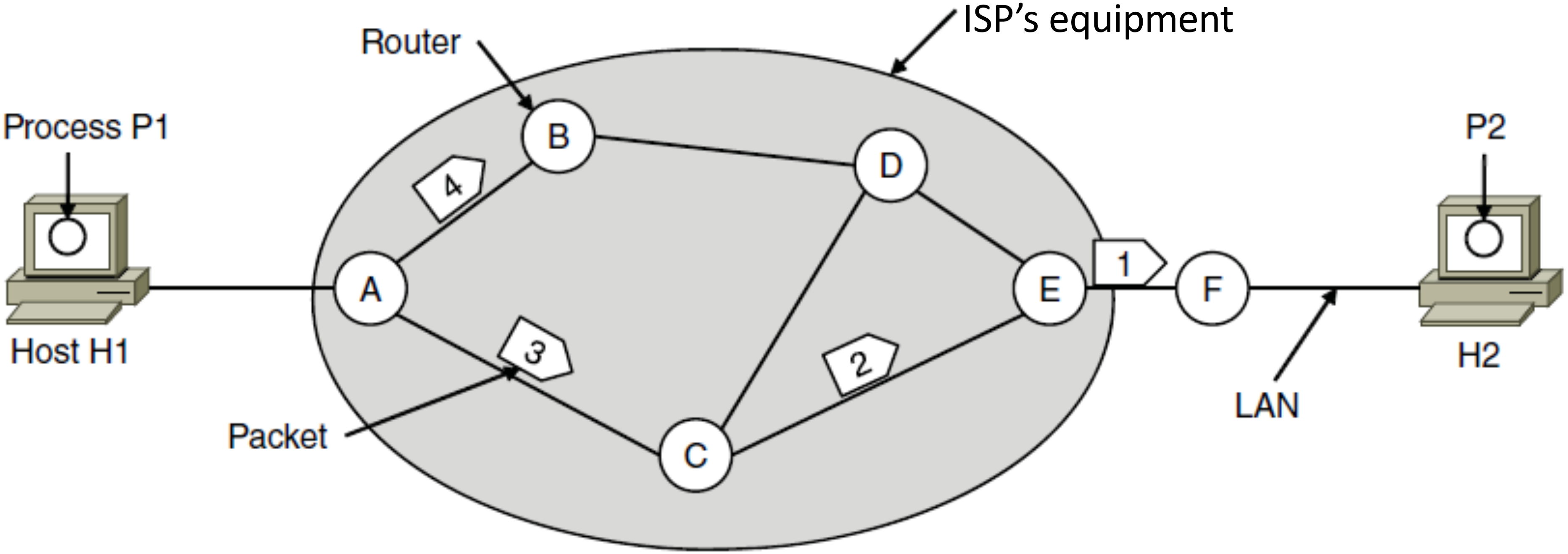
Two Network Service Models

- Datagrams, or connectionless service
  - Like postal letters
  - (IP as an example)

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

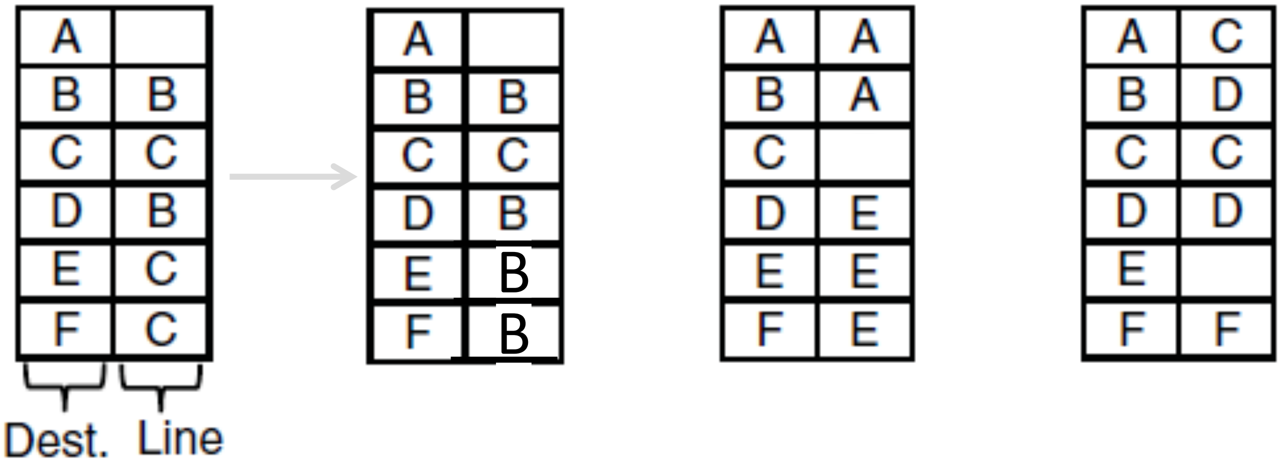
Datagram Model

- Packets contain a destination address; each router uses it to forward packets, maybe 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.	Line
A	
B	B
C	C
D	B
E	C
F	C

A's table (later)

A	
B	B
C	C
D	B
E	B
F	B

C's Table

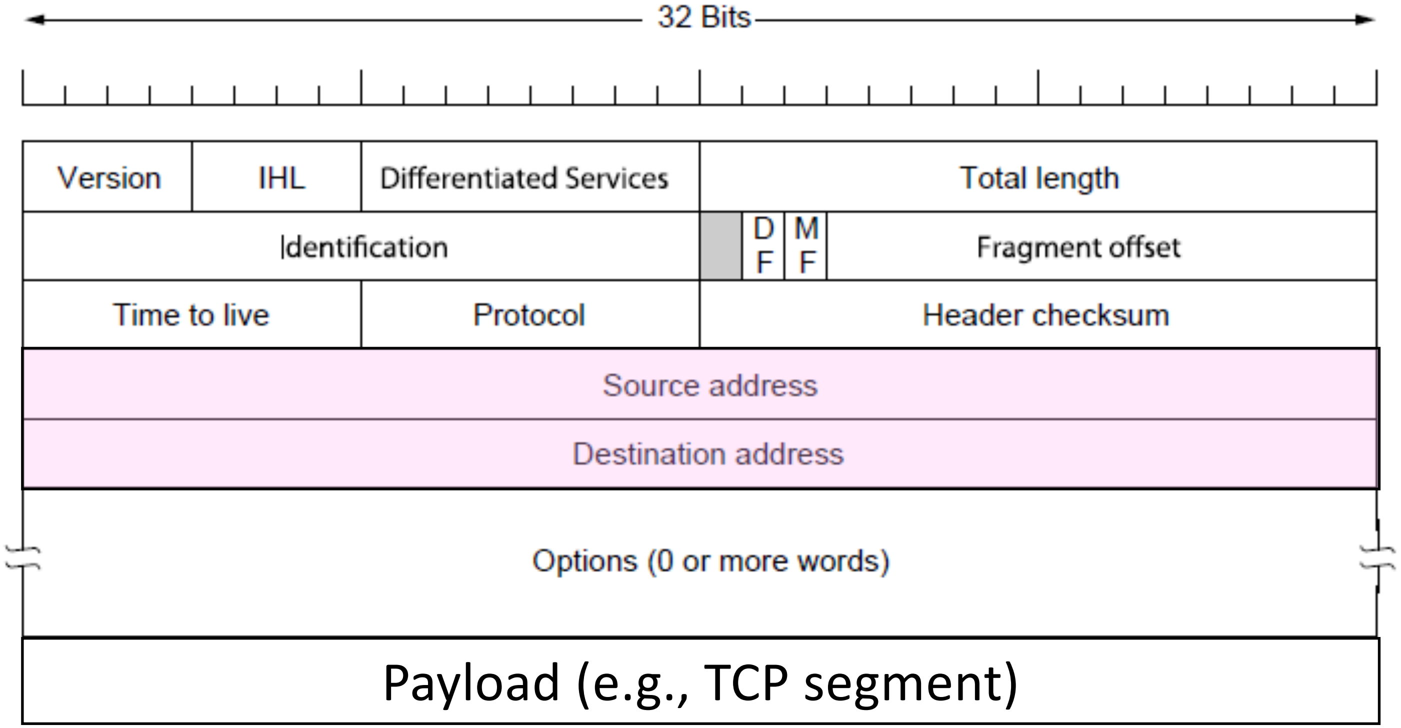
A	A
B	A
C	
D	E
E	E
F	E

E's Table

A	C
B	D
C	C
D	D
E	
F	F

IP (Internet Protocol)

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



32 Bits

Version | IHL | Differentiated Services | Total length

Identification | D F | M F | Fragment offset

Time to live | Protocol | Header checksum

Source address

Destination address

Options (0 or more words)

Payload (e.g., TCP segment)

Datagrams vs Virtual Circuits

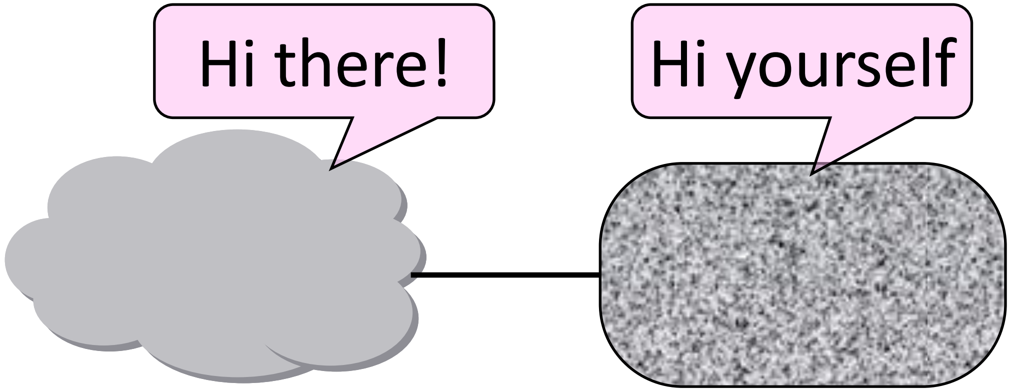
- Complementary strengths

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

Internetworking (IP)

Topic

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



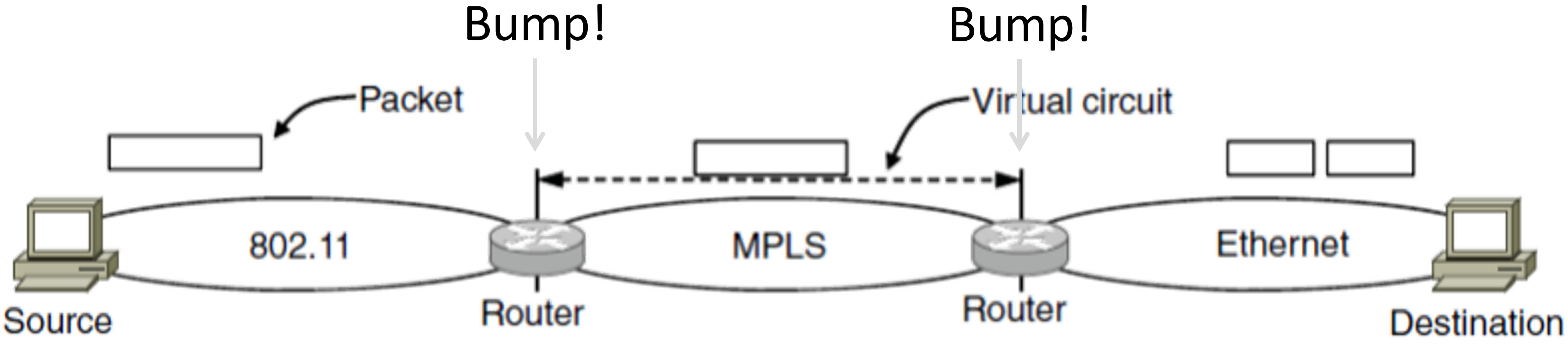
How Networks May Differ

- 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

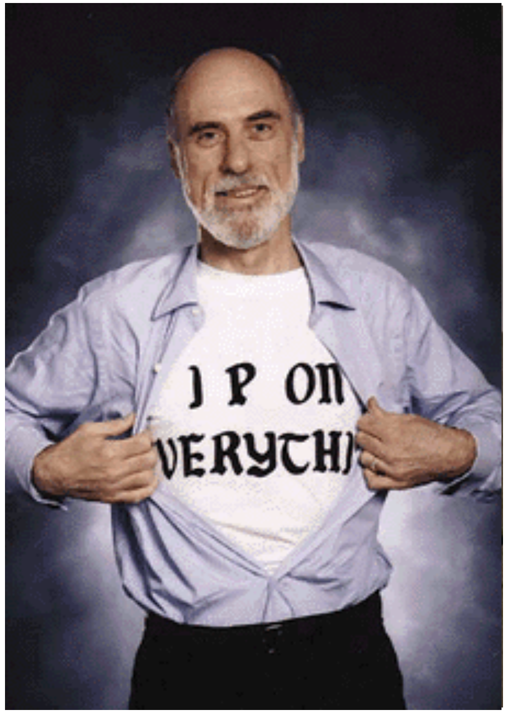


Bump! Bump!

Internetworking – Cerf and Kahn

- Pioneers: Cerf and Kahn
  - "Fathers of the Internet"
  - In 1974, later led to TCP/IP
- Tackled the problems of interconnecting networks
  - Instead of mandating a single technology

Vint Cerf



Bob Kahn

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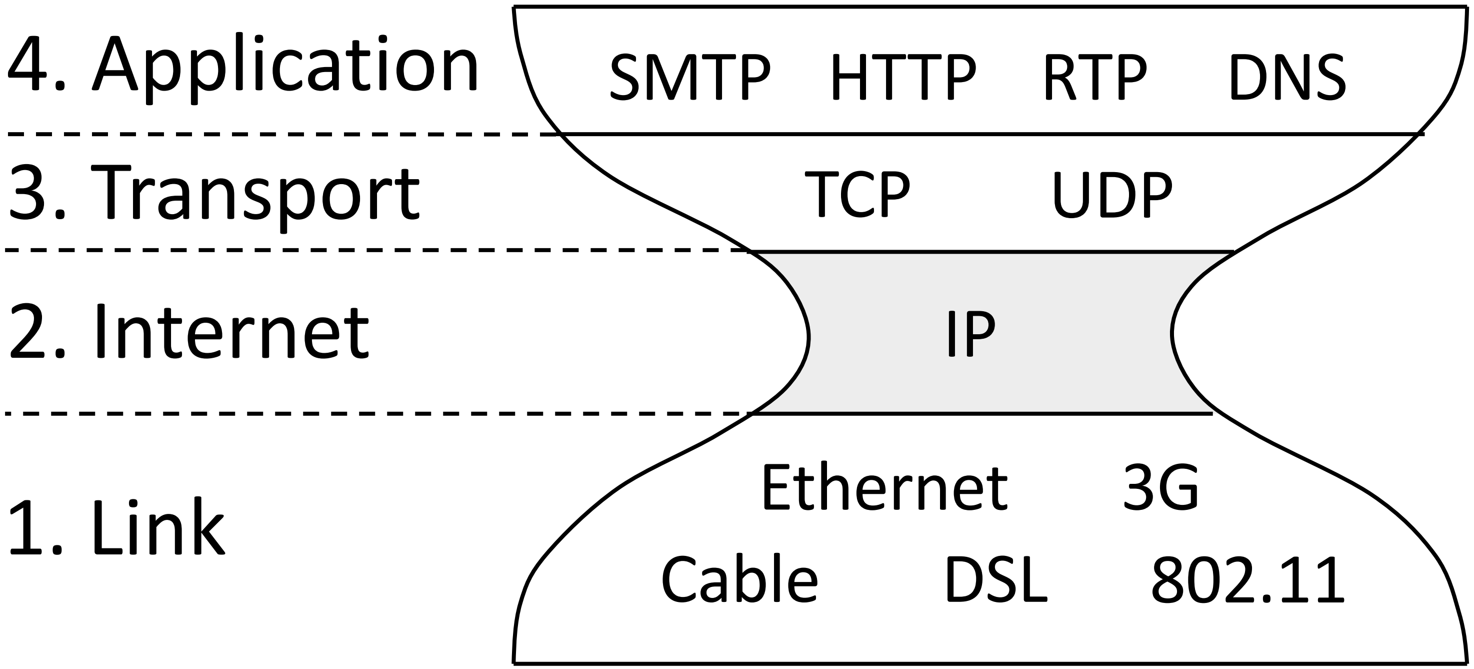
Internet Reference Model

- Internet Protocol (IP) is the "narrow waist"
  - Supports many different links below and apps above

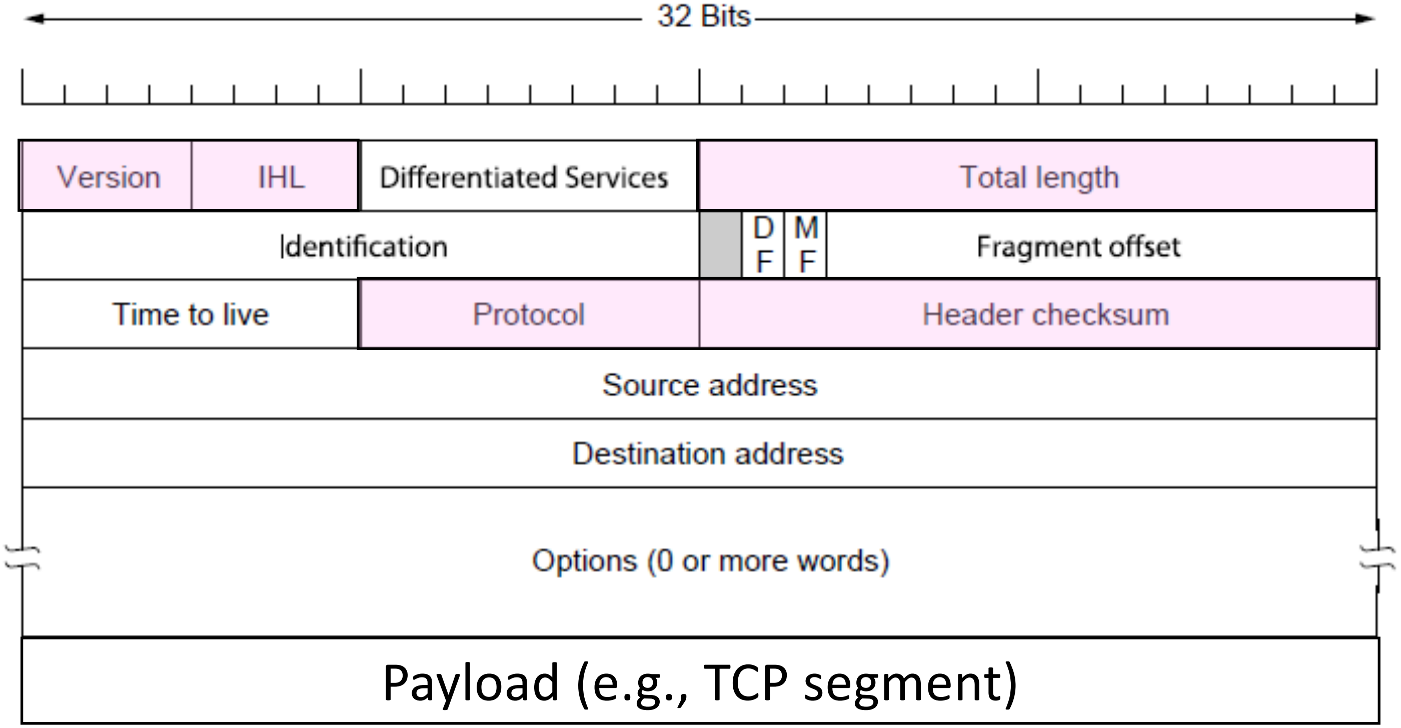


IP as a Lowest Common Denominator

- Suppose only some networks support QOS or security etc.
  - Difficult for internetwork to support
- Pushes IP to be a “lowest common denominator”
  - 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), Total length, Protocol, and Header Checksum



32 Bits

Version
IHL
Differentiated Services
Total length

Identification
DF
MF
Fragment offset

Time to live
Protocol
Header checksum

Source address

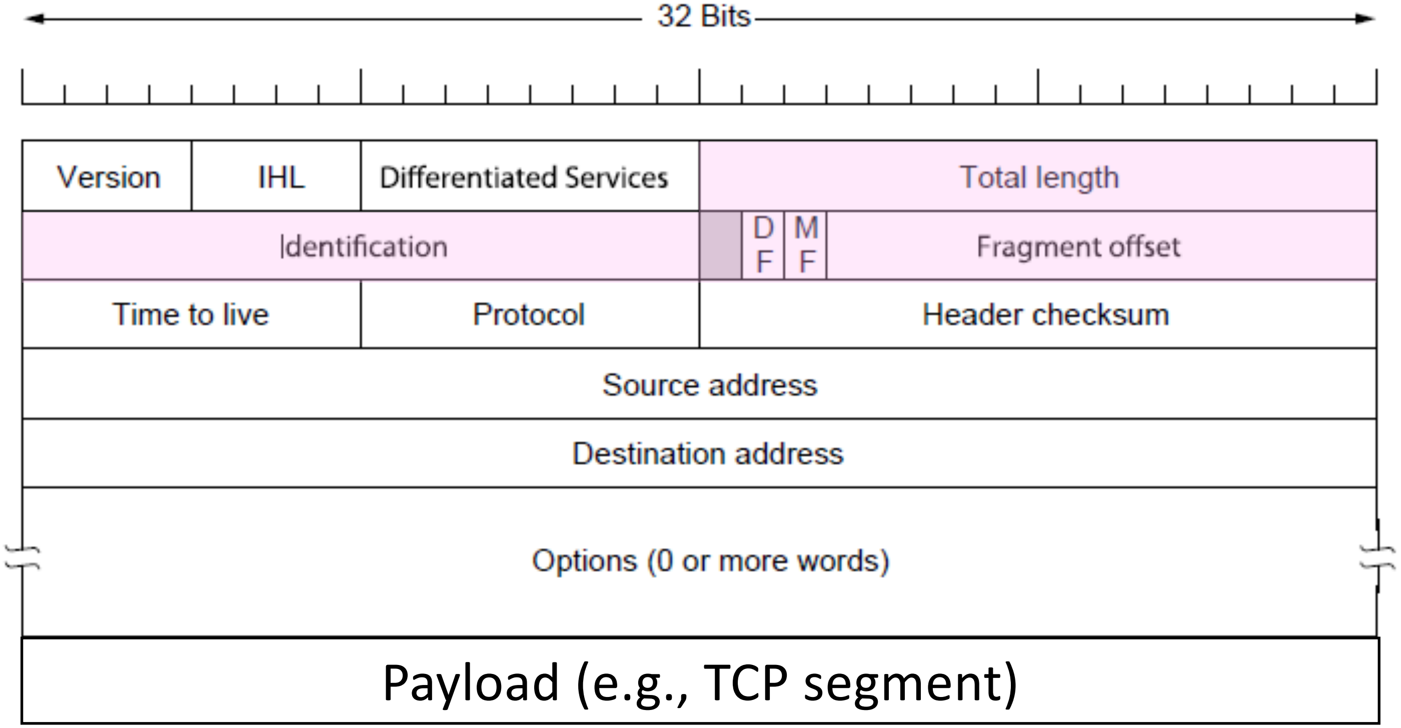
Destination address

Options (0 or more words)

Payload (e.g., TCP segment)

IPv4 (2)

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



32 Bits

Version

IHL

Differentiated Services

Total length

Identification

D F

M F

Fragment offset

Time to live

Protocol

Header checksum

Source address

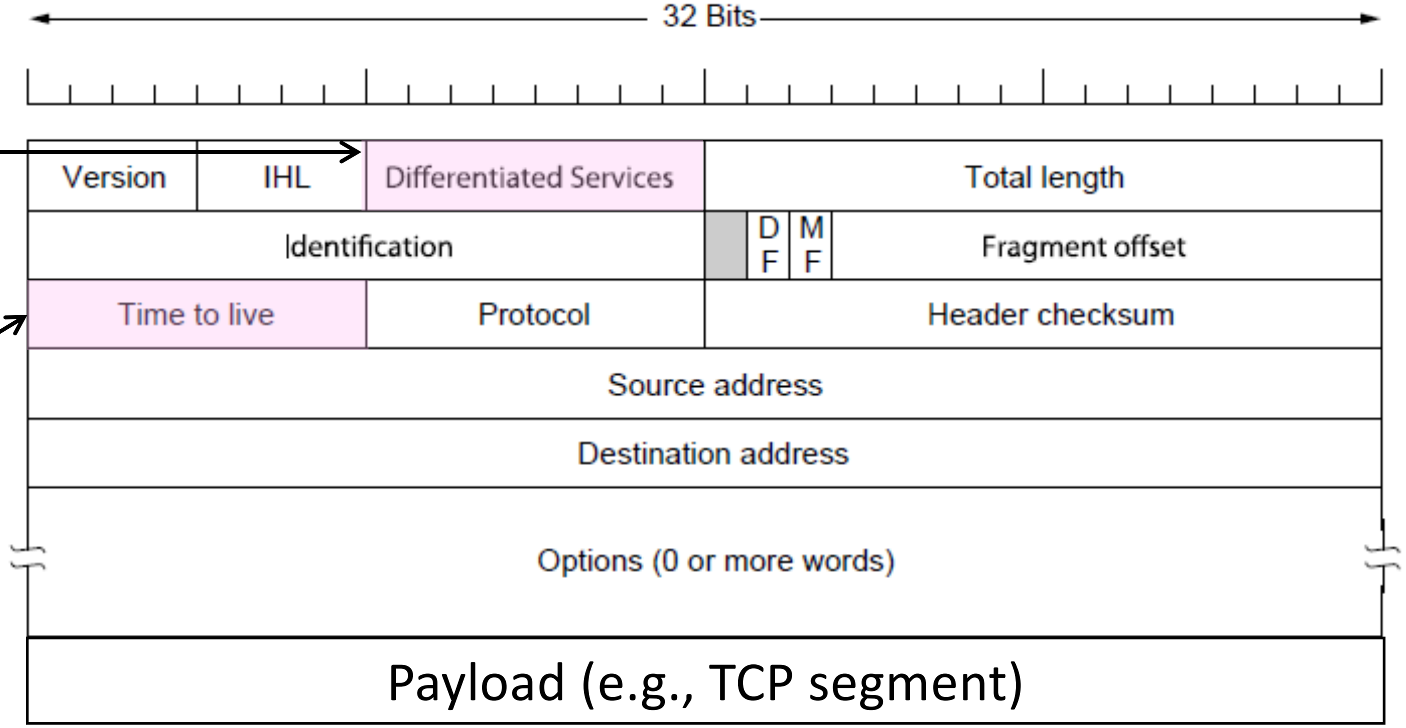
Destination address

Options (0 or more words)

Payload (e.g., TCP segment)

IPv4 (3)

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

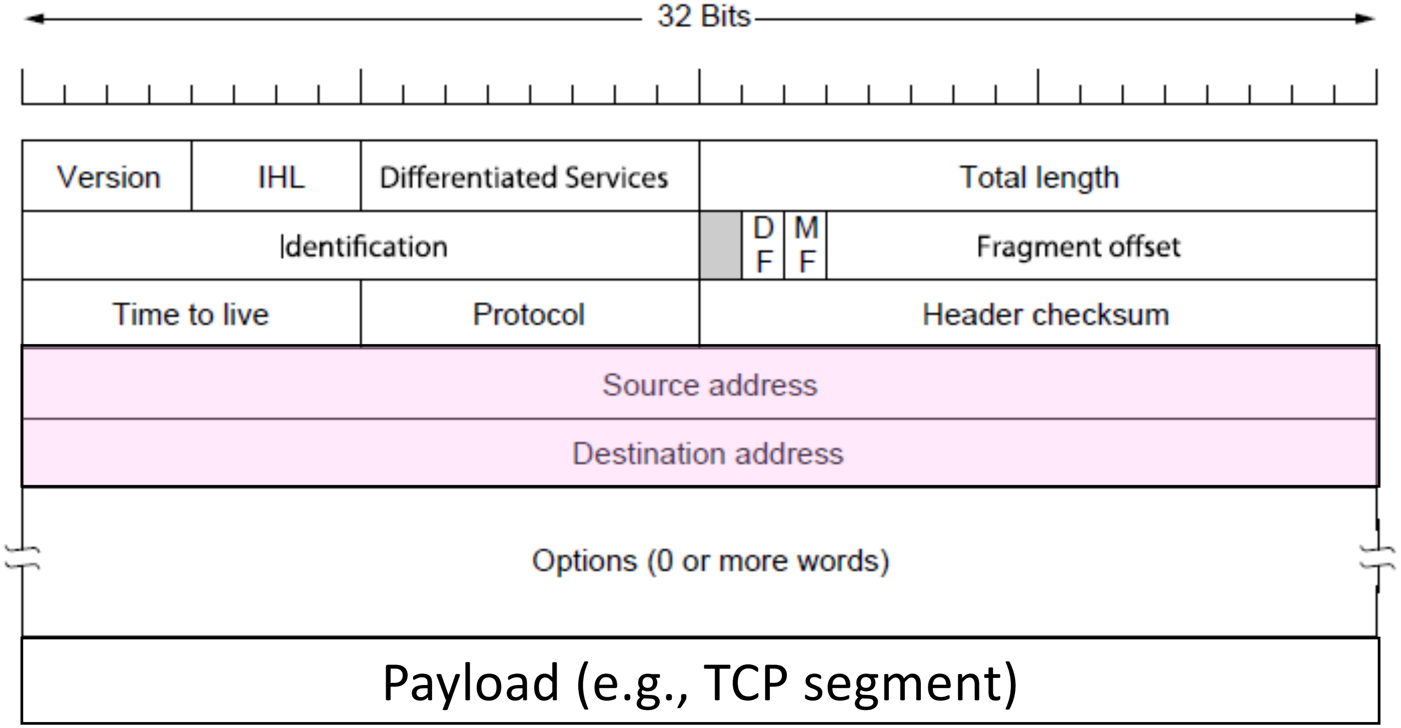


Later, with QOS

Later, with ICMP

IPv4 (4)

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



32 Bits

Version | IHL | Differentiated Services | Total length

Identification | DF | MF | Fragment offset

Time to live | Protocol | Header checksum

Source address

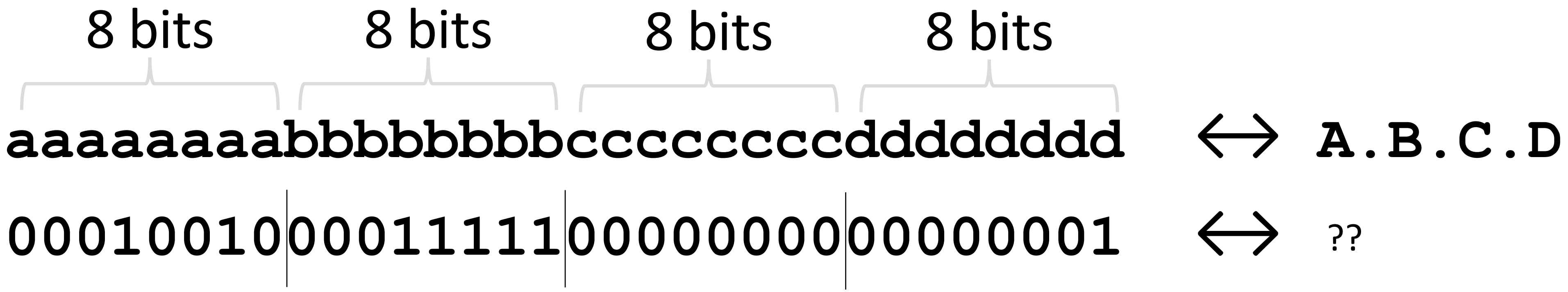
Destination address

Options (0 or more words)

Payload (e.g., TCP segment)

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



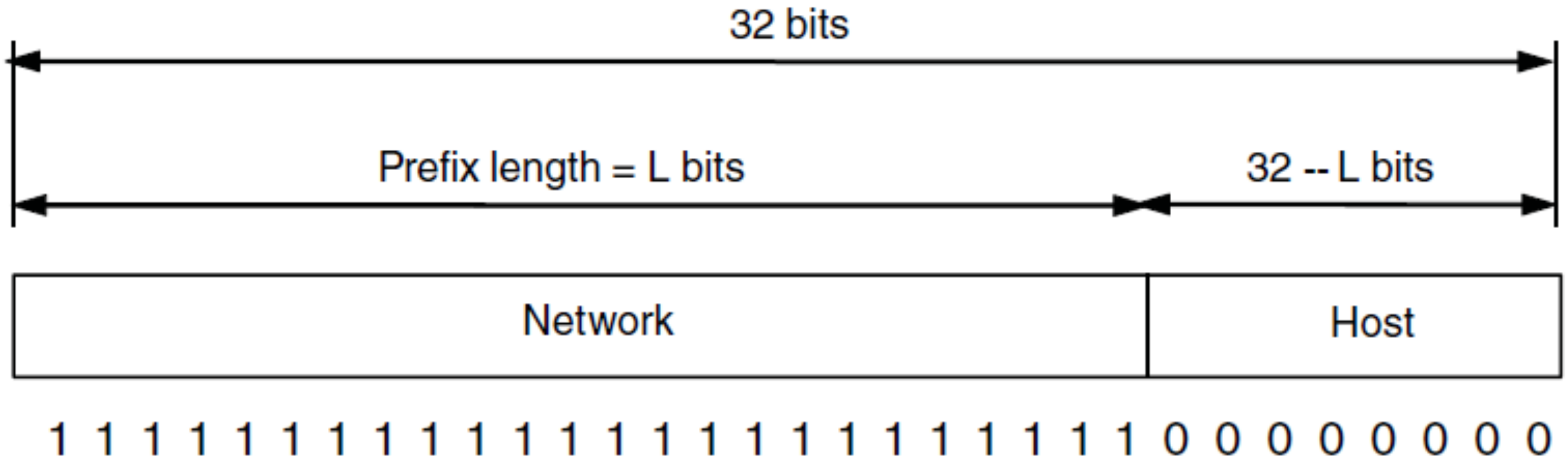
8 bits 8 bits 8 bits 8 bits

`aaaaaaaabbbbbbbbccccccccdddddddd` ↔ `A.B.C.D`

00010010|00011111|00000000|00000001 ↔ ??

IP Prefixes

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



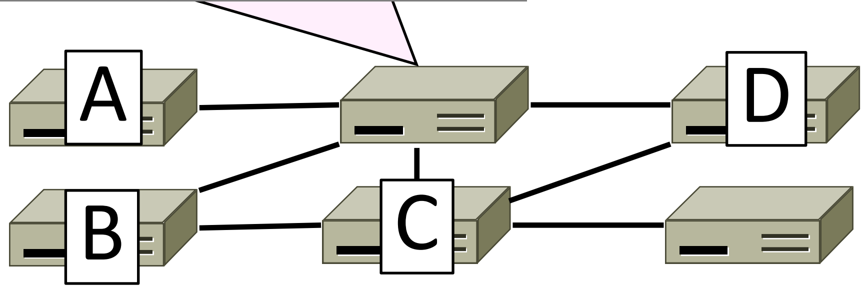
IP Prefixes (2)

- Written in “IP 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 /32 is 1 address

IP Forwarding

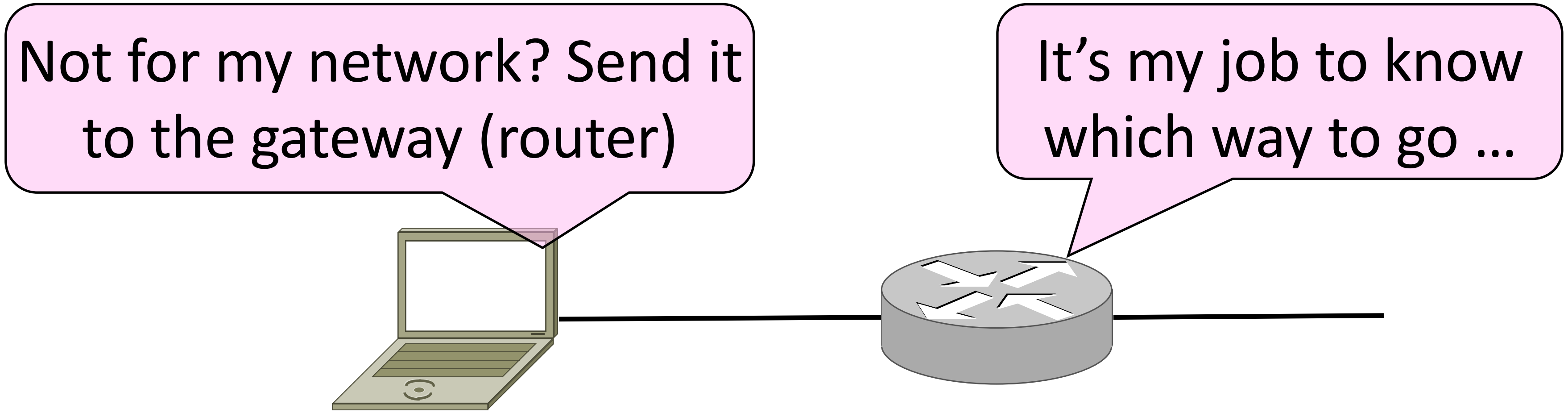
- Nodes use a table that lists the next hop for prefixes
- Lookup the destination address’s prefix in the table

Prefix	Next Hop
102.24.0.0/19	D
192.24.12.0/22	B



Host/Router Distinction

- In the Internet:
  - Routers do the routing, know way to all destinations
  - Hosts send remote traffic (out of prefix) to nearest router

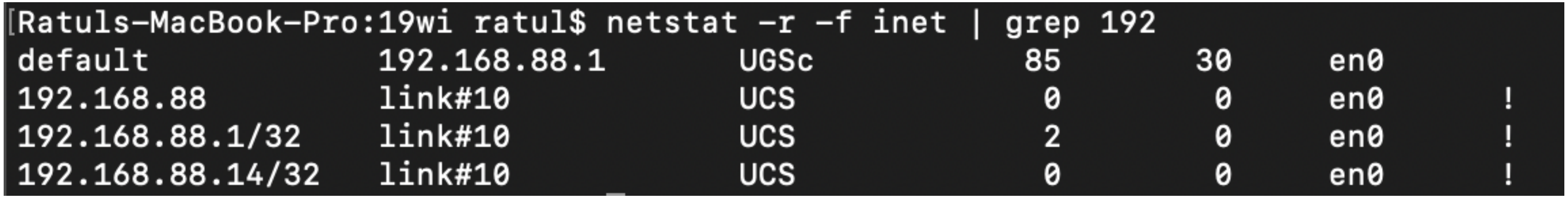

Not for my network? Send it to the gateway (router)
It’s my job to know which way to go …

Host Networking

- Consists of 4 pieces of data:
  - IP Address
  - Subnet Mask
    - Defines local addresses
  - Gateway
    - Who (local) to send non-local packets to for routing
  - DNS Server (Later)

Host Forwarding Table

Prefix	**Next Hop**
My network prefix	Send on local link
Default (0.0.0.0/0)	Send to my router



```
[Ratuls-MacBook-Pro:19wi ratul$ netstat -r -f inet | grep 192
 default             192.168.88.1       UGSc              85        30      en0
 192.168.88          link#10            UCS                0         0      en0        !
 192.168.88.1/32     link#10            UCS                2         0      en0        !
 192.168.88.14/32    link#10            UCS                0         0      en0        !
```

Issues?

- Where does this break down?

Bootstrapping (DHCP)

Finding Link nodes (ARP)

Really big packets (Fragmentation)

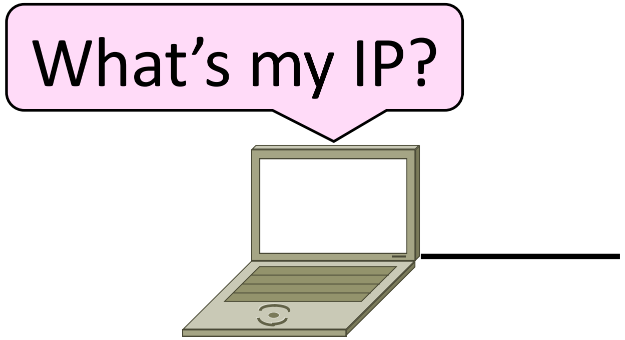
Errors in the network (ICMP)

Running out of addresses (IPv6, NAT)

Dynamic Host Configuration Protocol (DHCP)

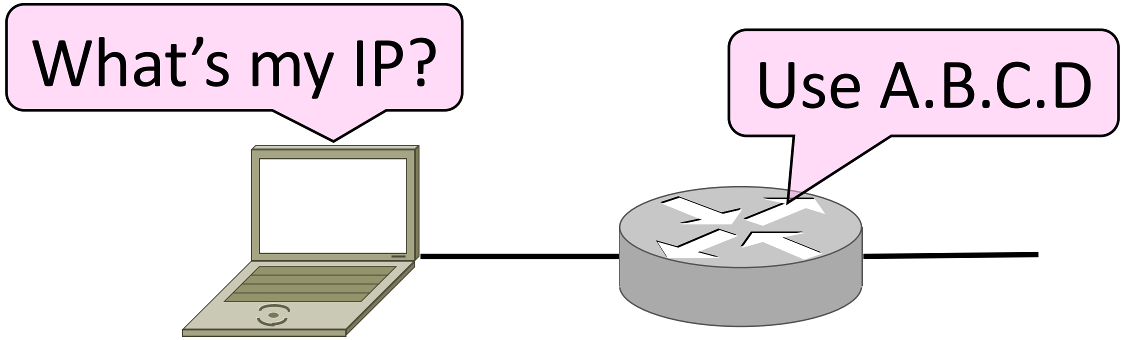
Bootstrapping

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



Bootstrapping (2)

1. Manual configuration (old days)
   - Can’t be factory set, depends on use
2. DHCP: Automatically configure addresses

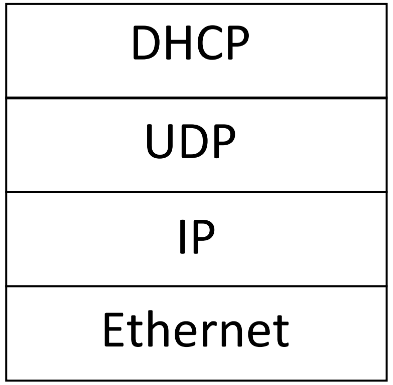


DHCP

- 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

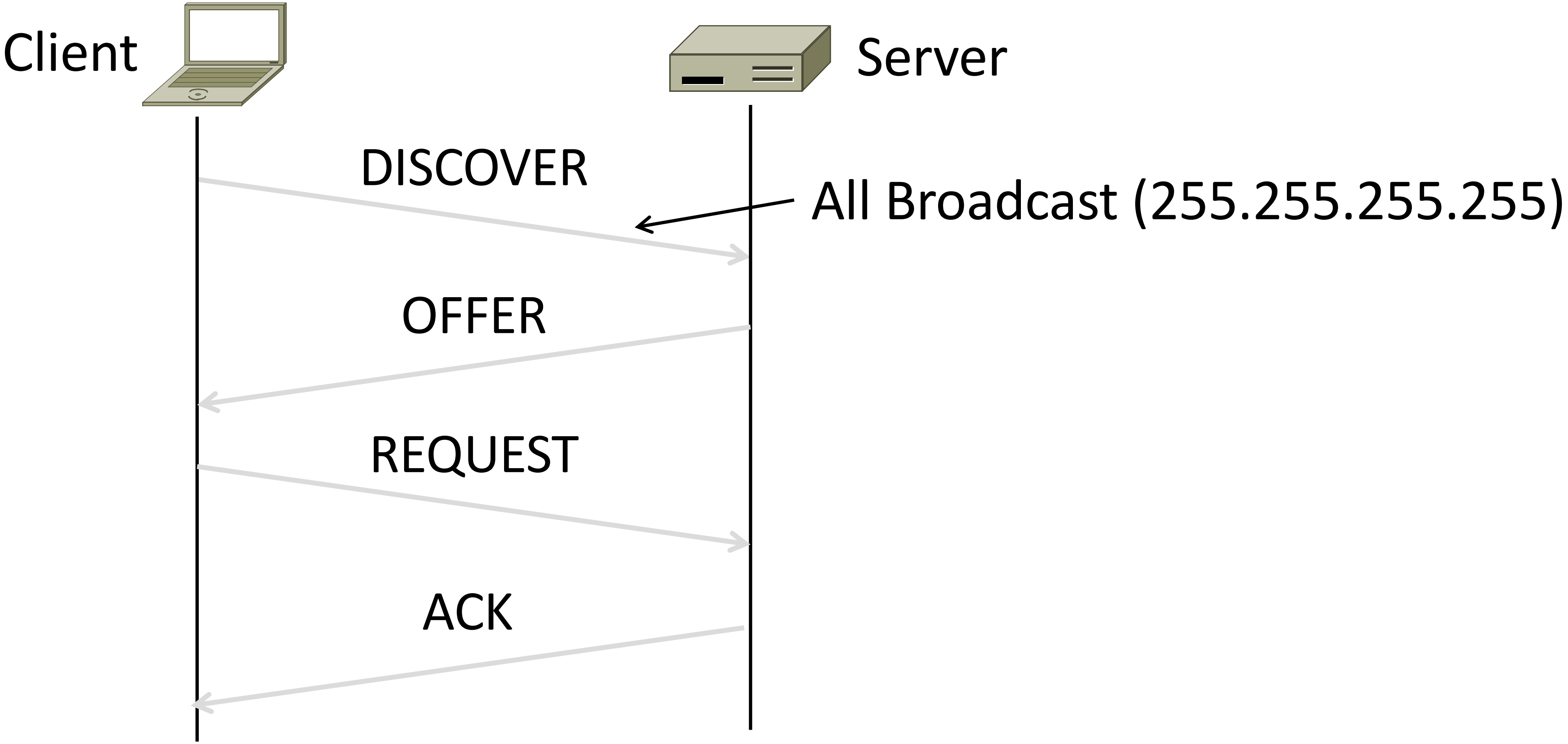
IP

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 link-level network
  - Broadcast address is all 1s
  - IP (32 bit): 255.255.255.255
  - Ethernet (48 bit): ff:ff:ff:ff:ff:ff

DHCP Messages



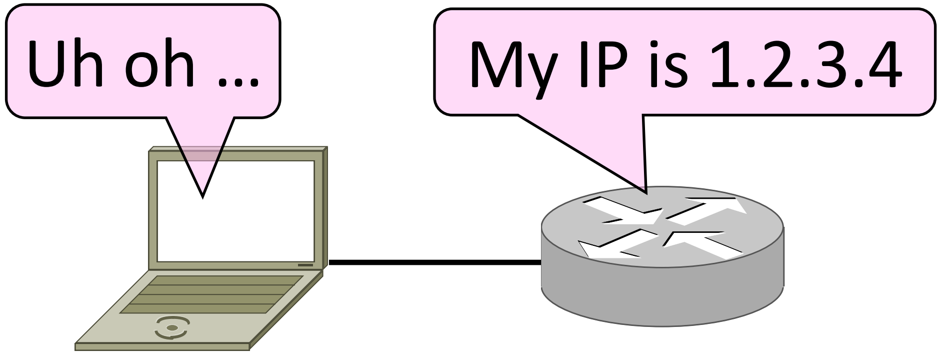
DHCP Messages (2)

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

Address Resolution Protocol (ARP)

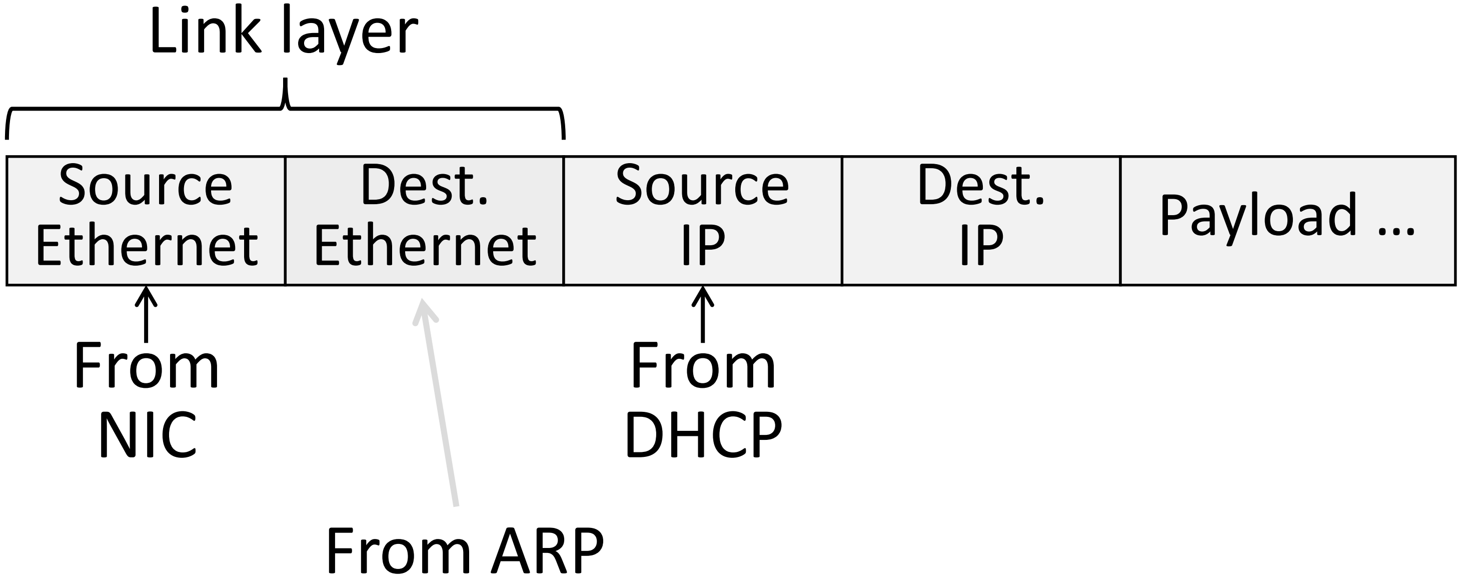
Sending an IP Packet

- 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



Link layer

Source Ethernet	Dest. Ethernet	Source IP	Dest. IP	Payload …

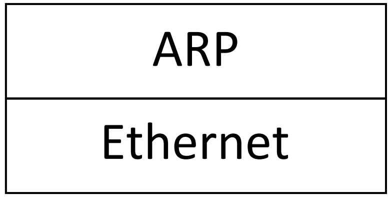
From NIC

From DHCP

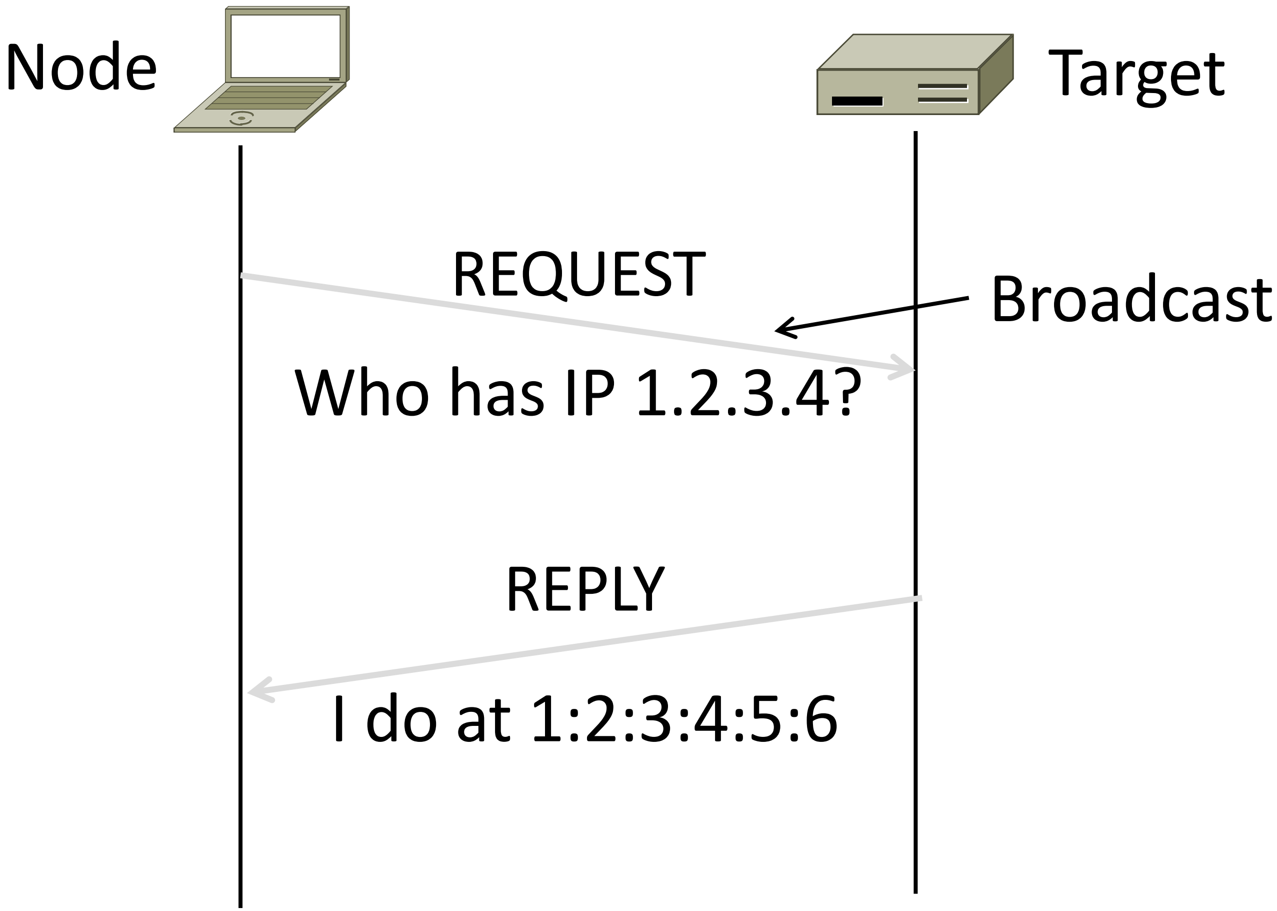
From ARP

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



Node

Target

REQUEST

Broadcast

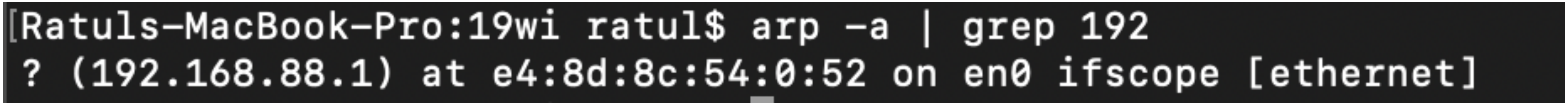
Who has IP 1.2.3.4?

REPLY

I do at 1:2:3:4:5:6

```
[root@host ~]# tcpdump -lni any arp & ( sleep 1; arp -d 10.0.0.254; ping -c1 -n 10.0.0.254 )

listening on any, link-type LINUX_SLL (Linux cooked), capture size 96 bytes

17:58:02.155495 arp who-has 10.2.1.224 tell 10.2.1.253

17:58:02.317444 arp who-has 10.0.0.96 tell 10.0.0.253

17:58:02.370446 arp who-has 10.3.1.12 tell 10.3.1.61
```

ARP Table



```
[Ratuls-MacBook-Pro:19wi ratul$ arp -a | grep 192
? (192.168.88.1) at e4:8d:8c:54:0:52 on en0 ifscope [ethernet]
```

Discovery Protocols

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