Recap of network layer

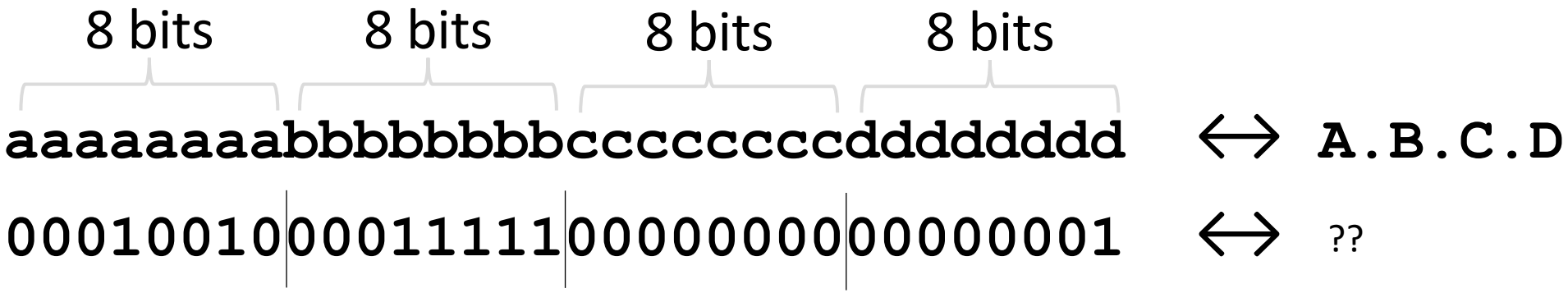
Needed to deliver packets to their destination

Solves three problems

- Internetworking
- Addressing
- Routing and forwarding

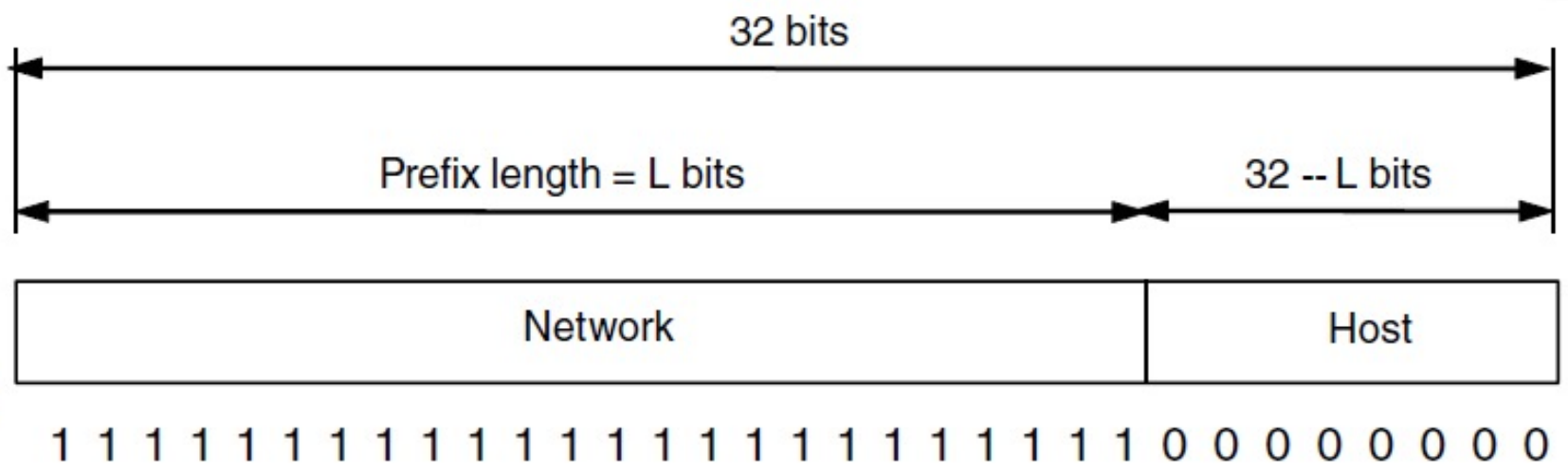
IP Addresses

- 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



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



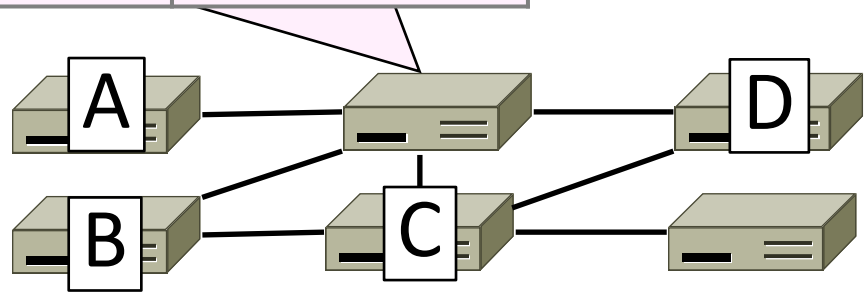
IP Prefixes (2)

- 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

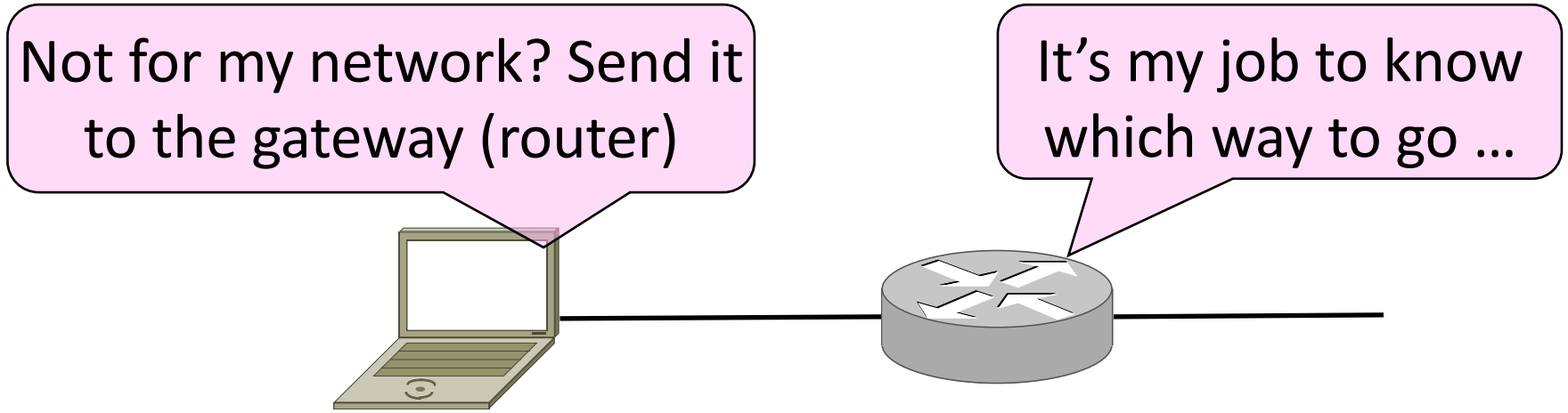
- Nodes use a table that lists the next hop for prefixes
- Lookup the destination address's prefix in the table

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



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?

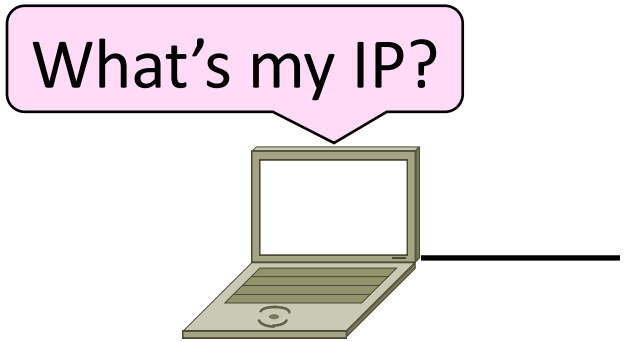
Bootstrapping (DHCP)

Finding Link nodes (ARP)

Dynamic Host Configuration Protocol (DHCP)

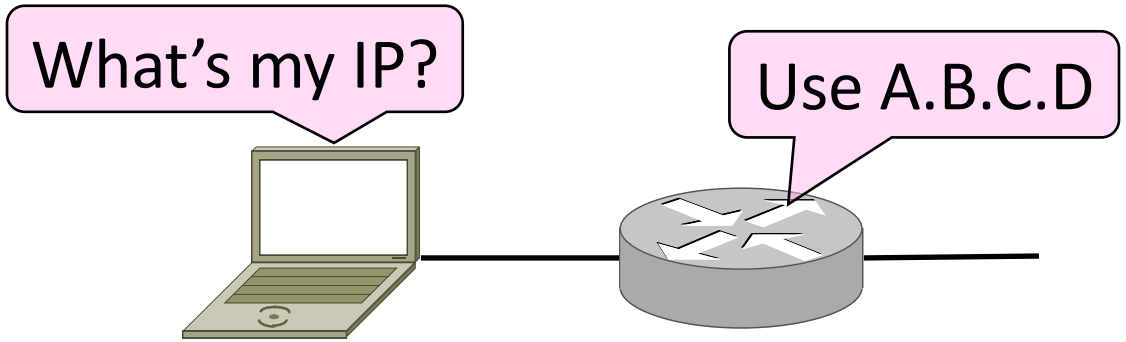
Bootstrapping

- 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

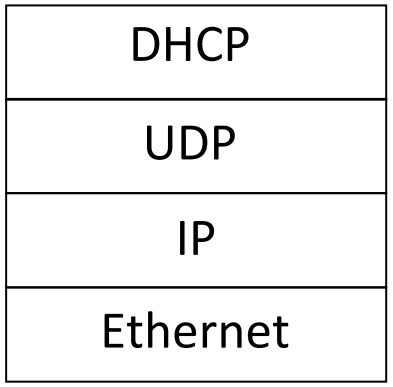


DHCP: Dynamic Host Configuration Protocol

- Invented around 1993, widely used now
- It leases IP address to nodes
- Provides other parameters too
  - Network prefix
  - Address of local router
  - DNS server, time server, etc.

DHCP Protocol Stack

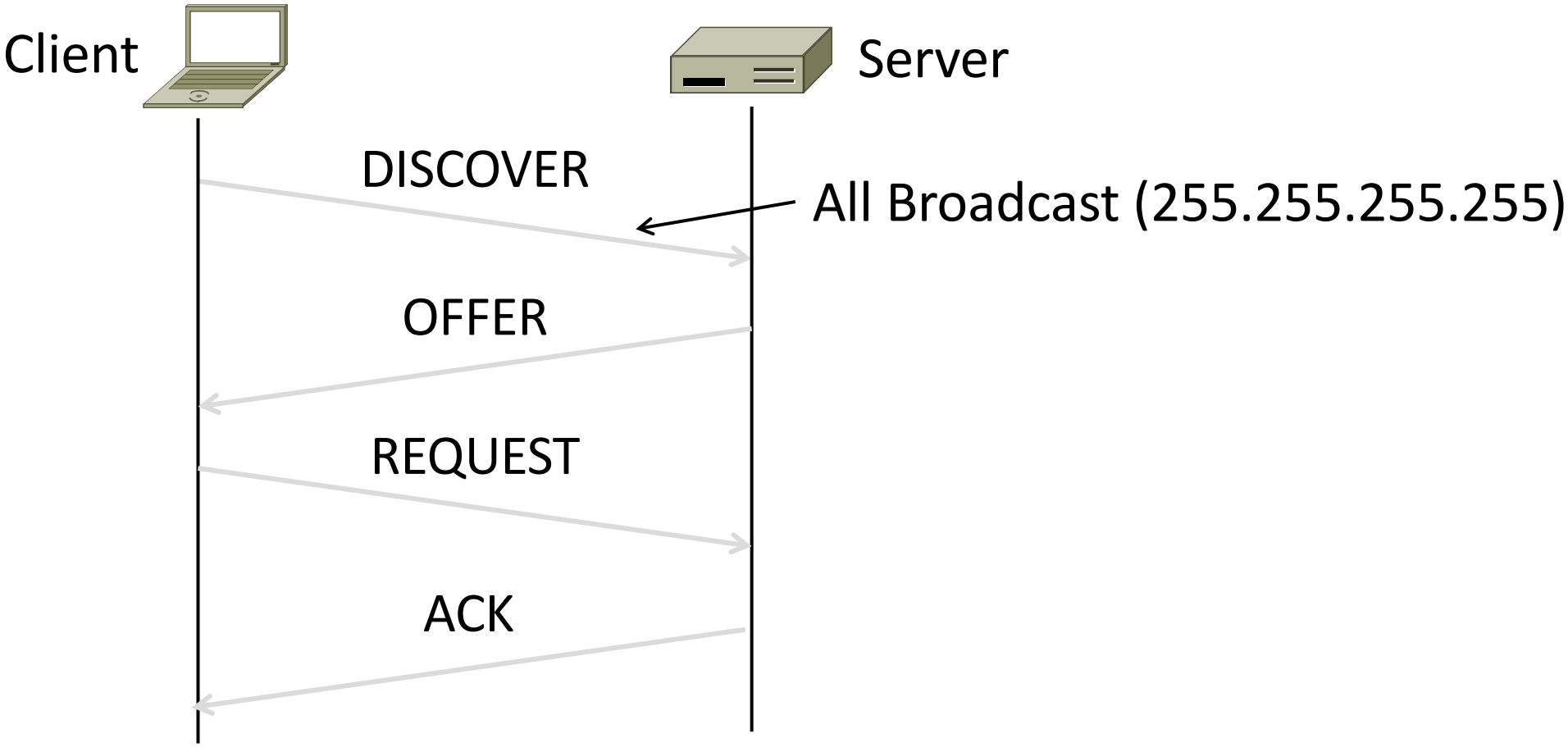
- DHCP is a client-server application
  - Uses UDP ports 67, 68



DHCP 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



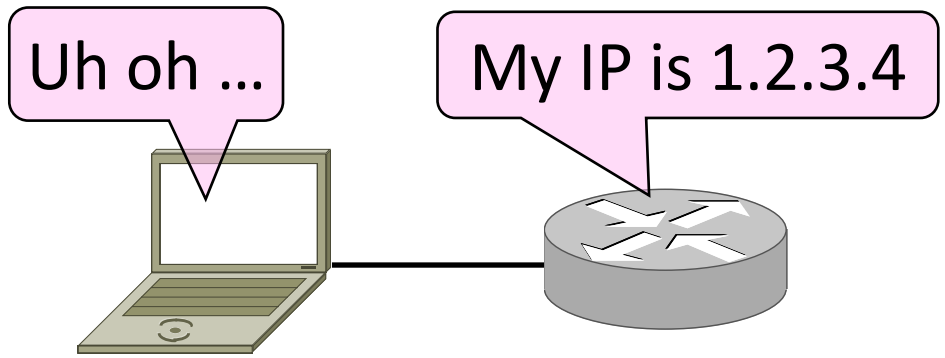
DHCP Messages (2)

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

Address Resolution Protocol (ARP)

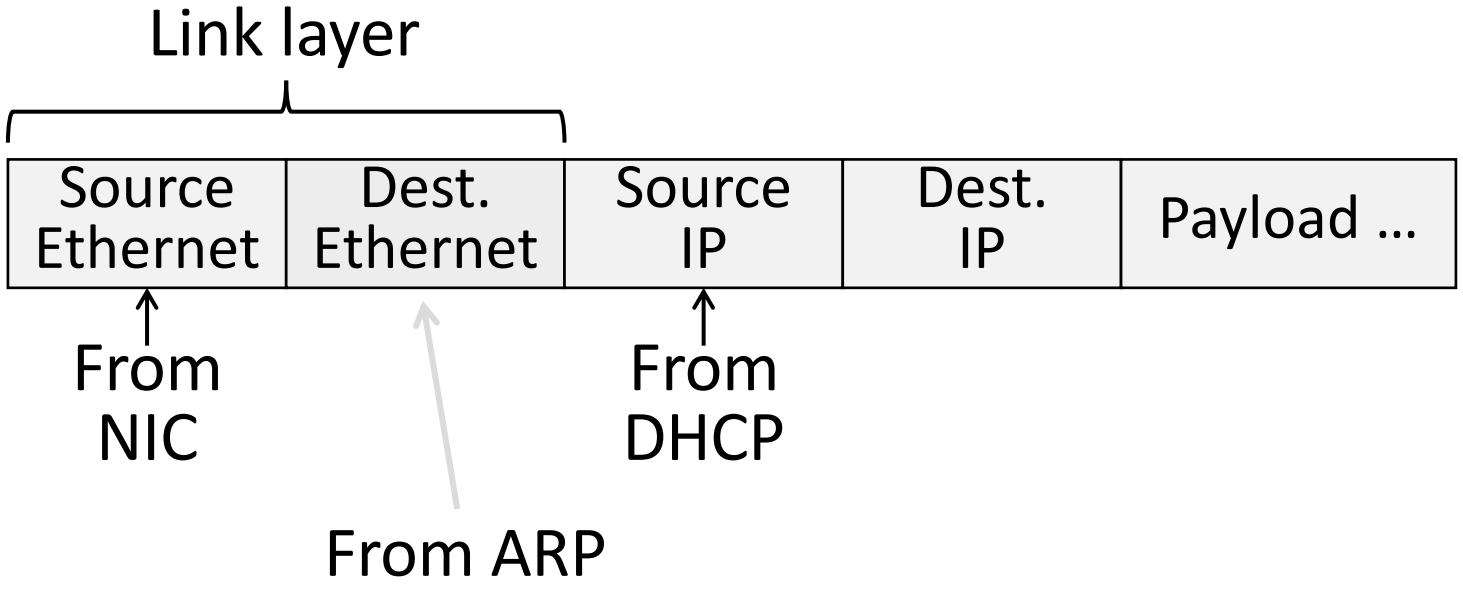
Sending an IP Packet

- 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?



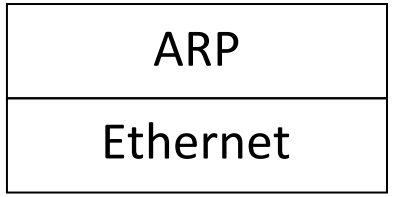
ARP (Address Resolution Protocol)

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

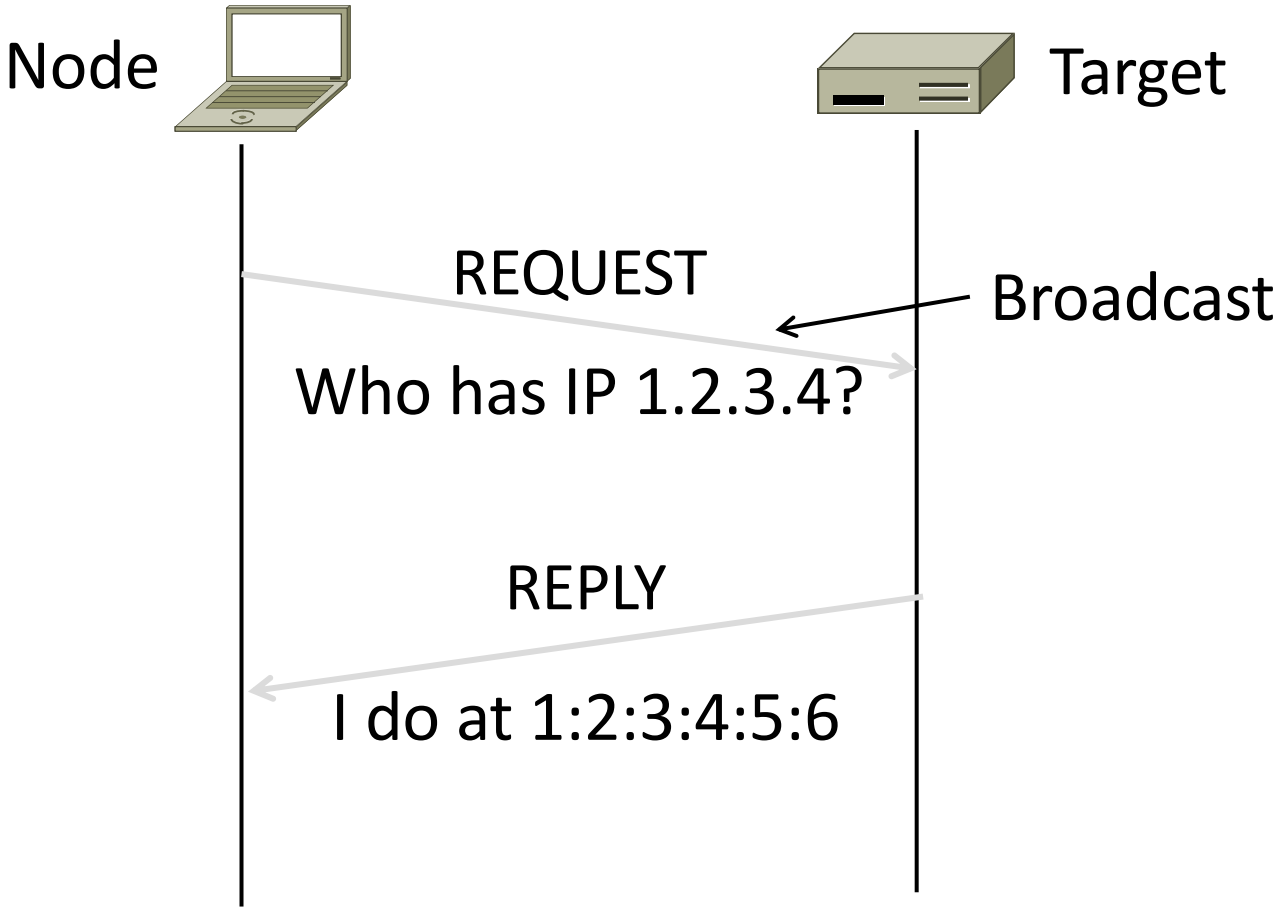


ARP Protocol Stack

- 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



[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]
```

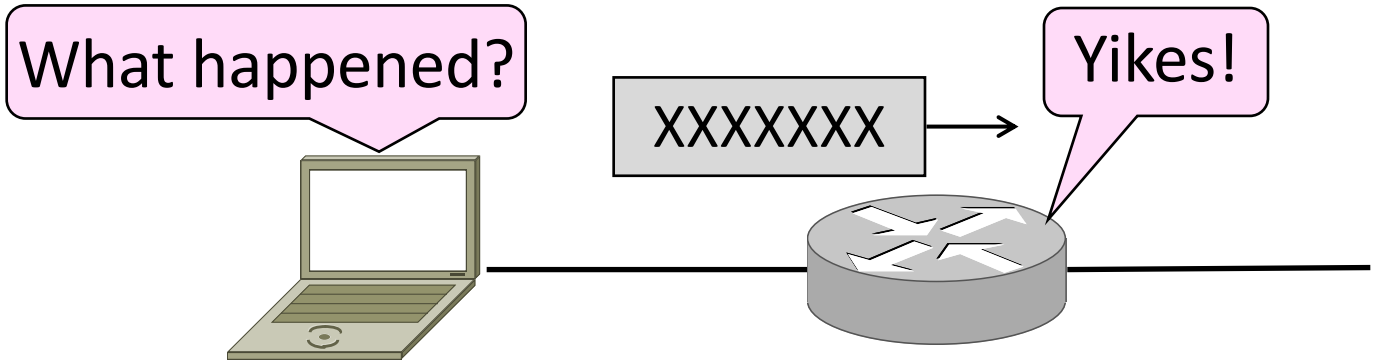
Discovery Protocols

- 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

Internet Control Message Protocol (ICMP)

Topic

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



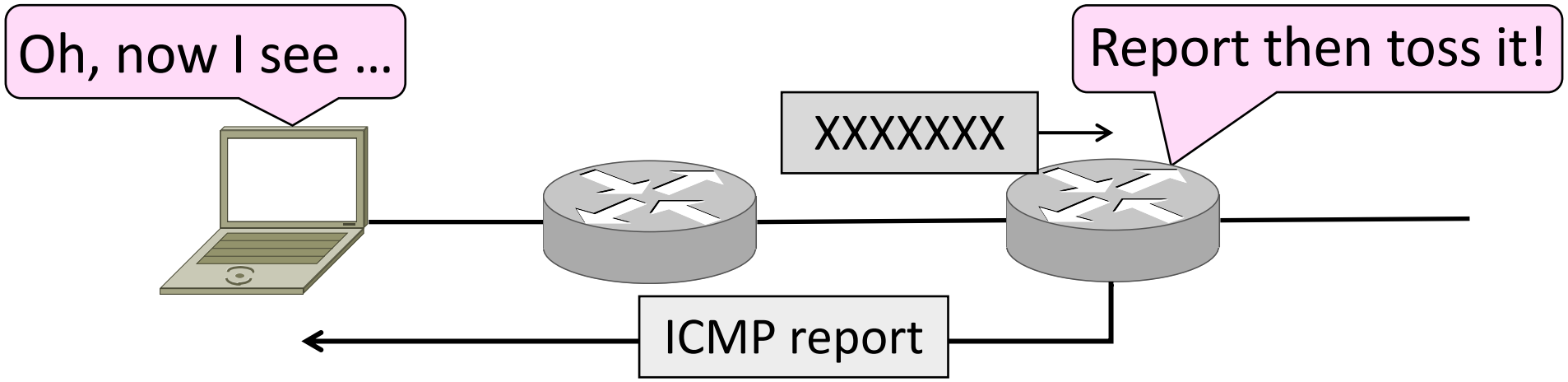
Internet Control Message Protocol

- 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

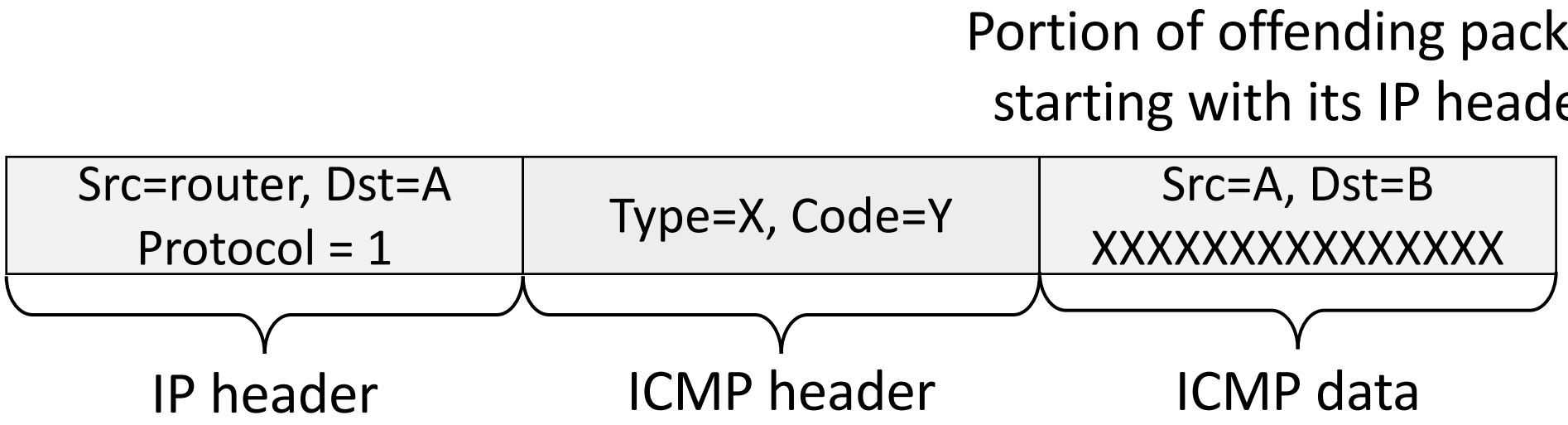
ICMP Errors

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



ICMP Message Format (2)

- 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



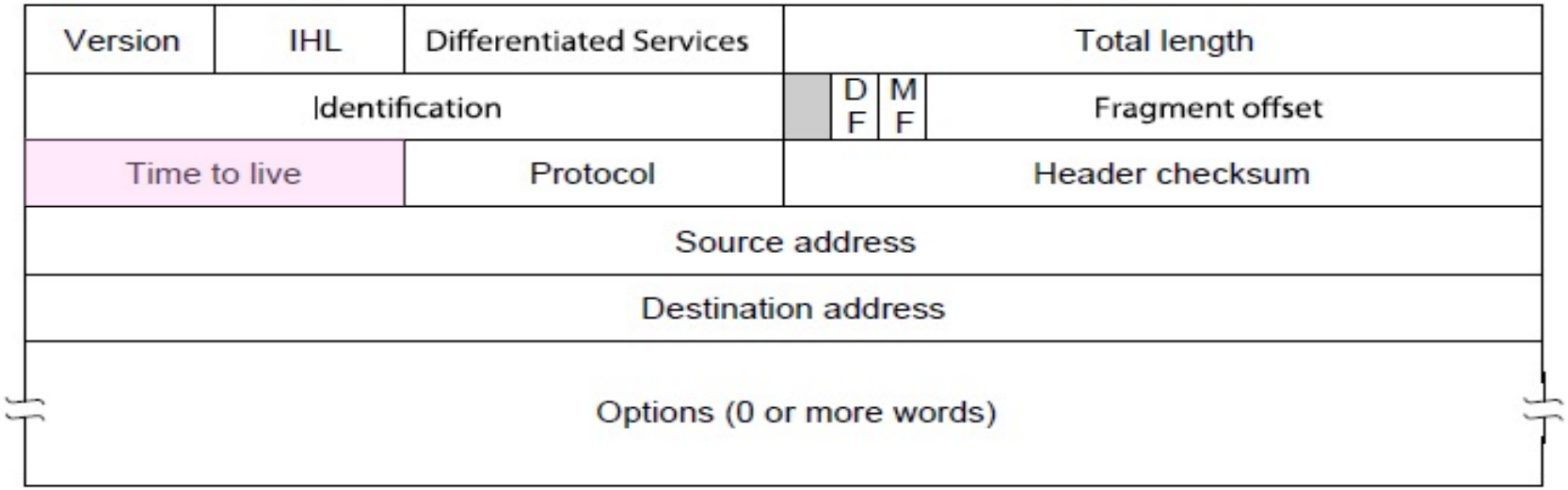
Example ICMP Messages

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

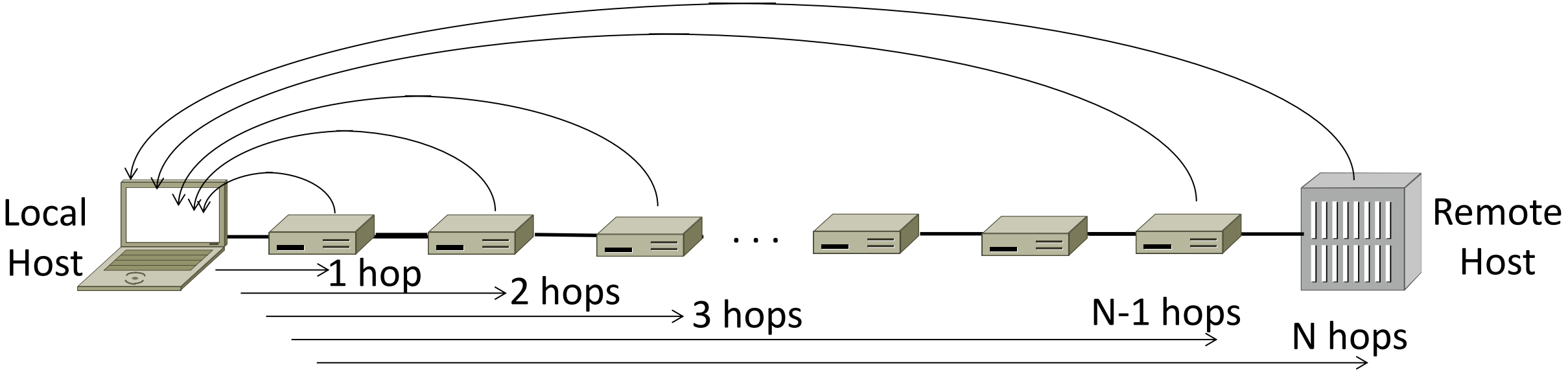
Traceroute

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



Traceroute (2)

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



Network Address Translation (NAT)

Problem: Internet's success

Today, Internet connects

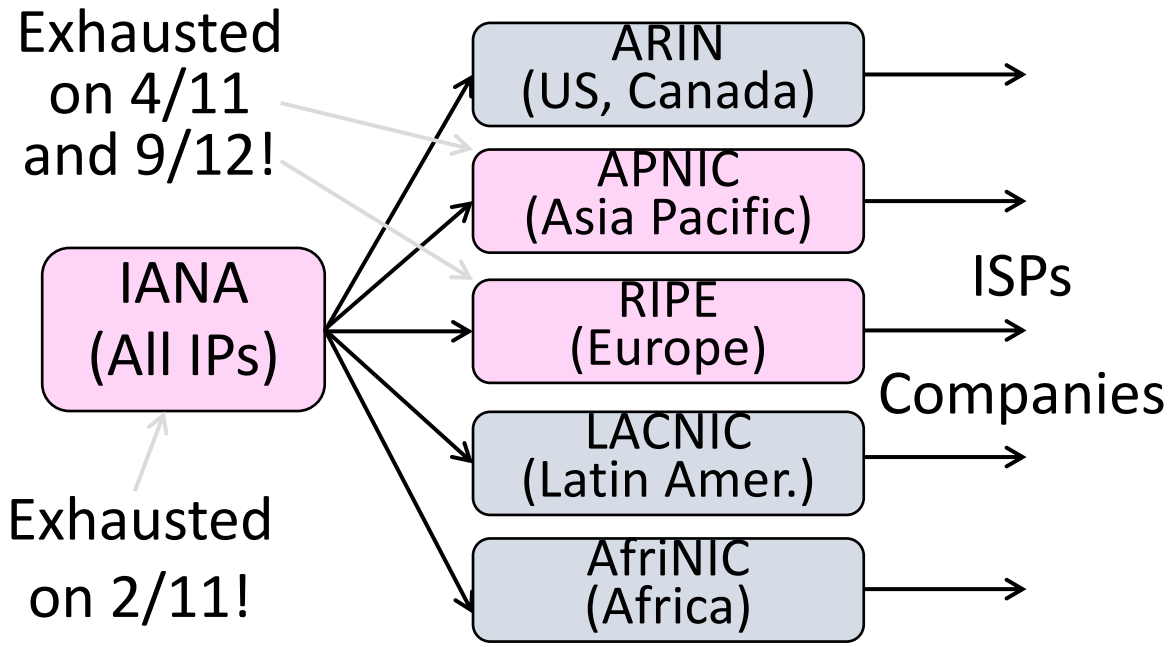
- 4B people
- 50B devices

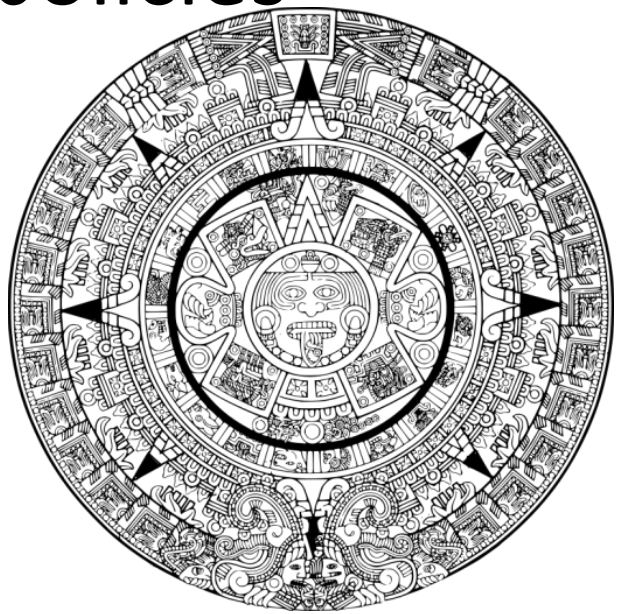
And we're using 32-bit addresses!

- 2B unique addresses

The End of New IPv4 Addresses

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





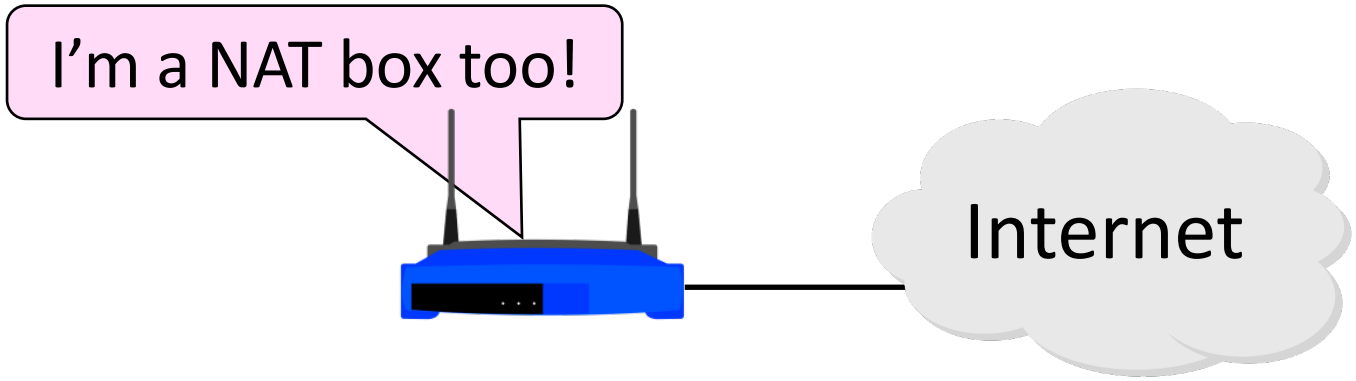
End of the world ? 12/21/12?

A market for IPv4 addresses

https://auctions.ipv4.global/prior-sales

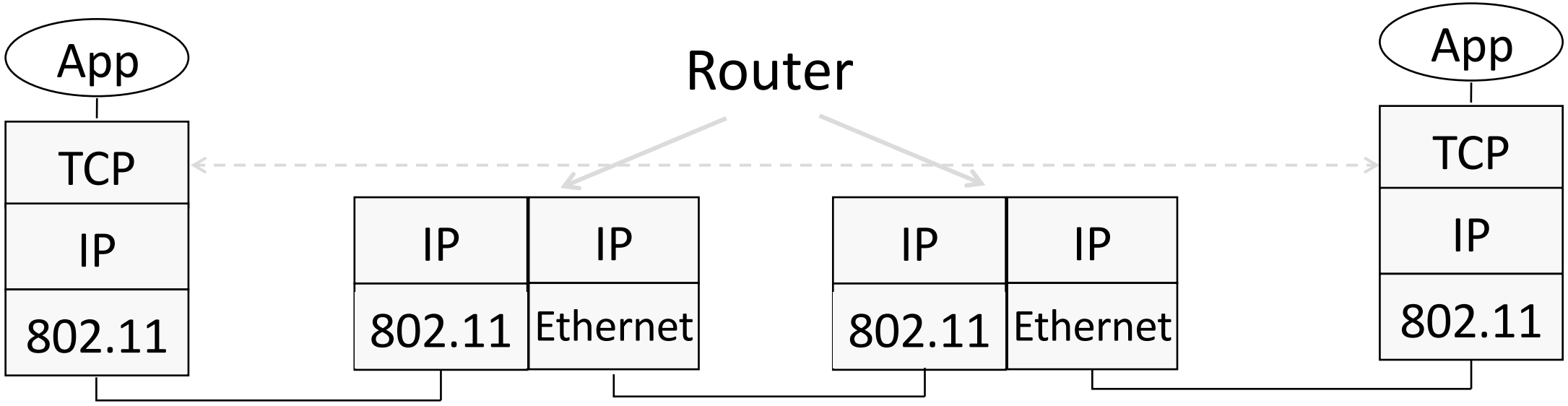
Solution 1: Network Address Translation (NAT)

- Basic idea: Map many “Private” IP addresses to one “Public” IP.
- Allocate IPs for private use (192.168.x, 10.x)



Layering Review

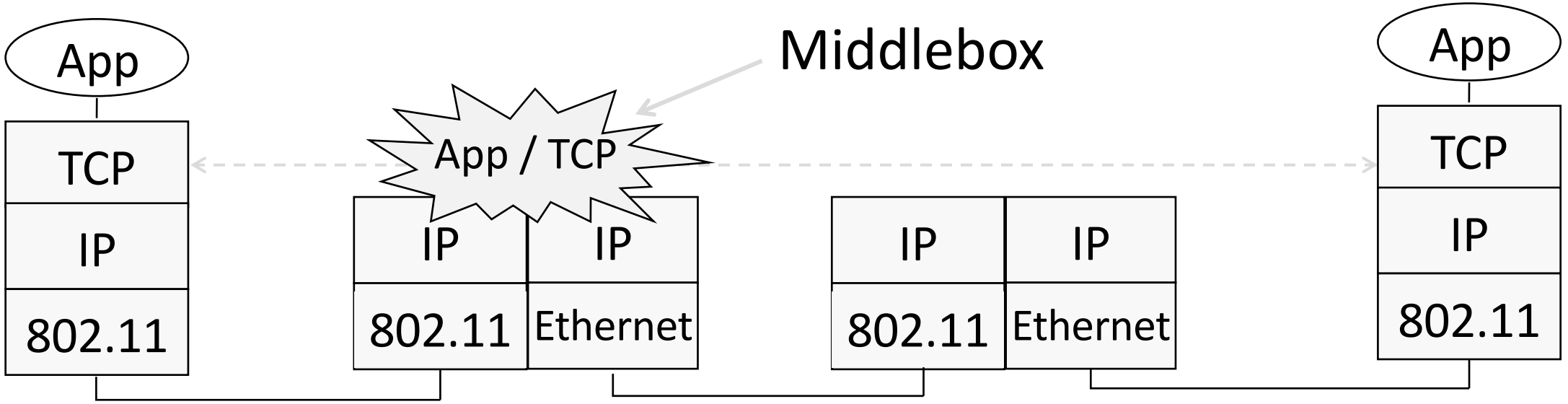
- Remember how layering is meant to work?
  - "Routers don't look beyond the IP header." Well …



Aside: Middleboxes

Sit “in the network” but do “more than IP” processing on packets to add new functionality

- NATs, Firewalls, Intrusion Detection Systems



Aside: Middleboxes (2)

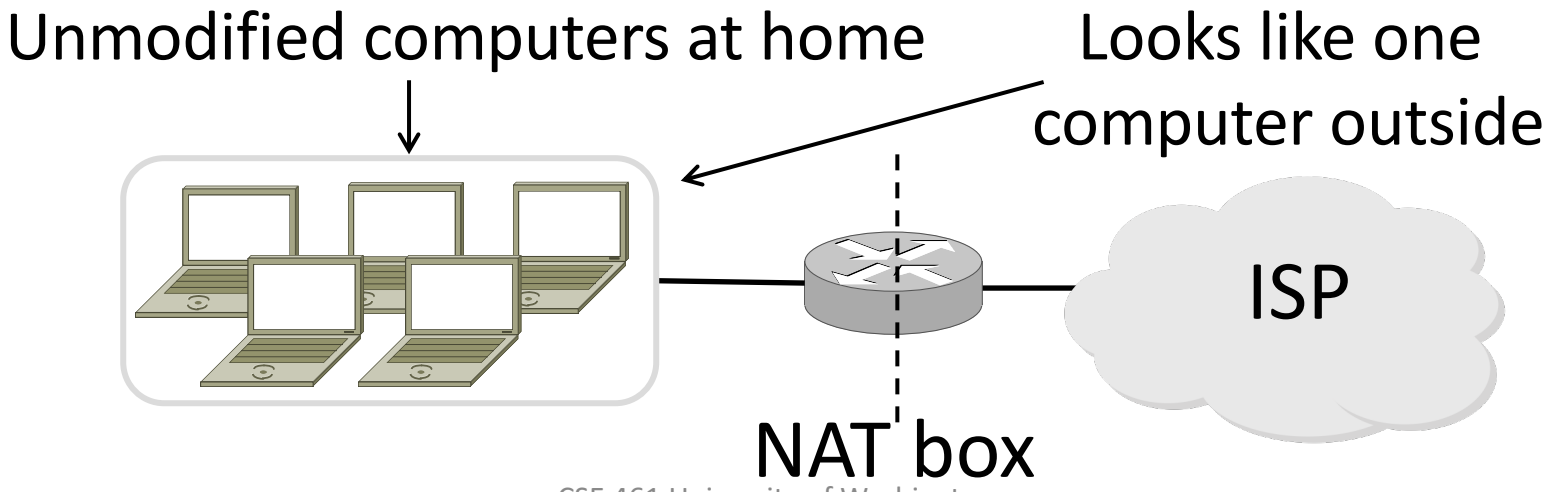
- Advantages
  - A possible rapid deployment path when no other option
  - Control over many hosts (IT)
- Disadvantages
  - Breaking layering interferes with connectivity
    - strange side effects
  - Poor vantage point for many tasks

NAT (Network Address Translation) Box

- NAT box maps an internal IP to an external IP
  - Many internal hosts 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 translation table

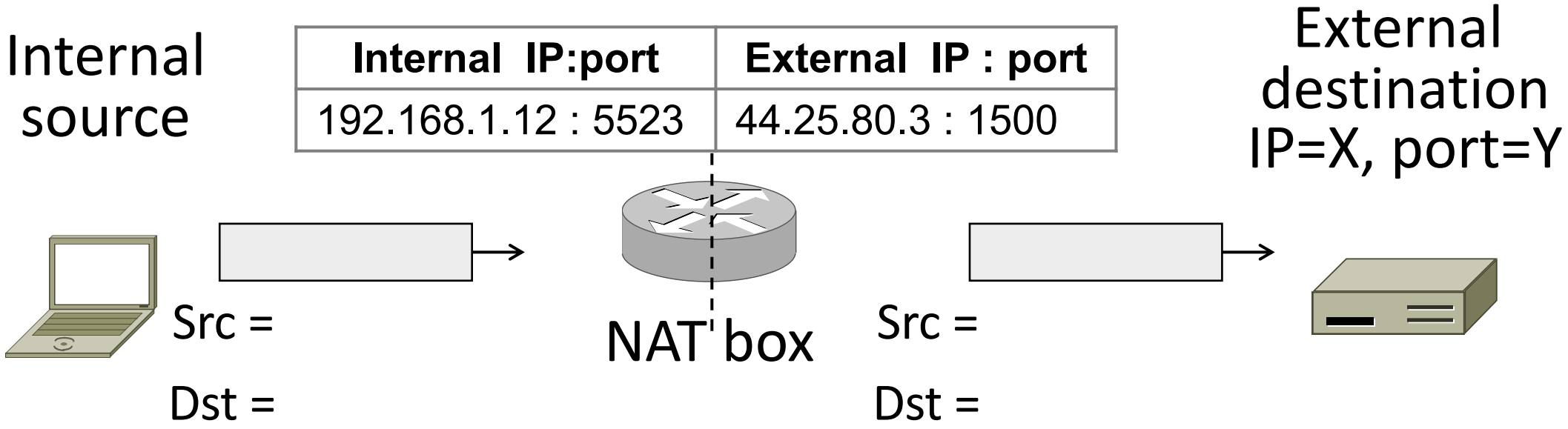
- Typically uses IP address + TCP port
- This is address and port translation

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

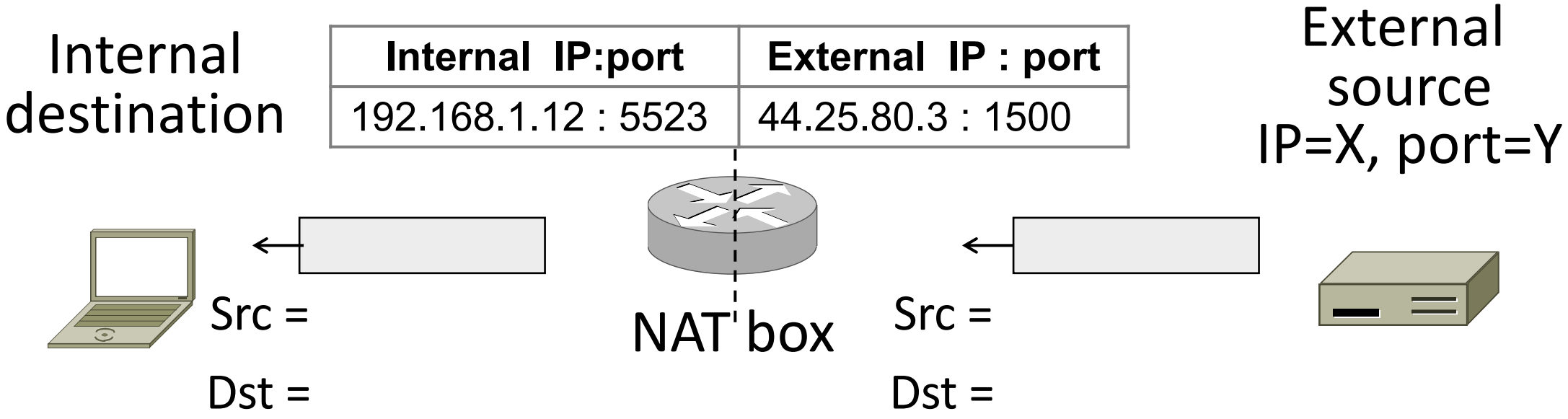
How NAT Works (2)

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



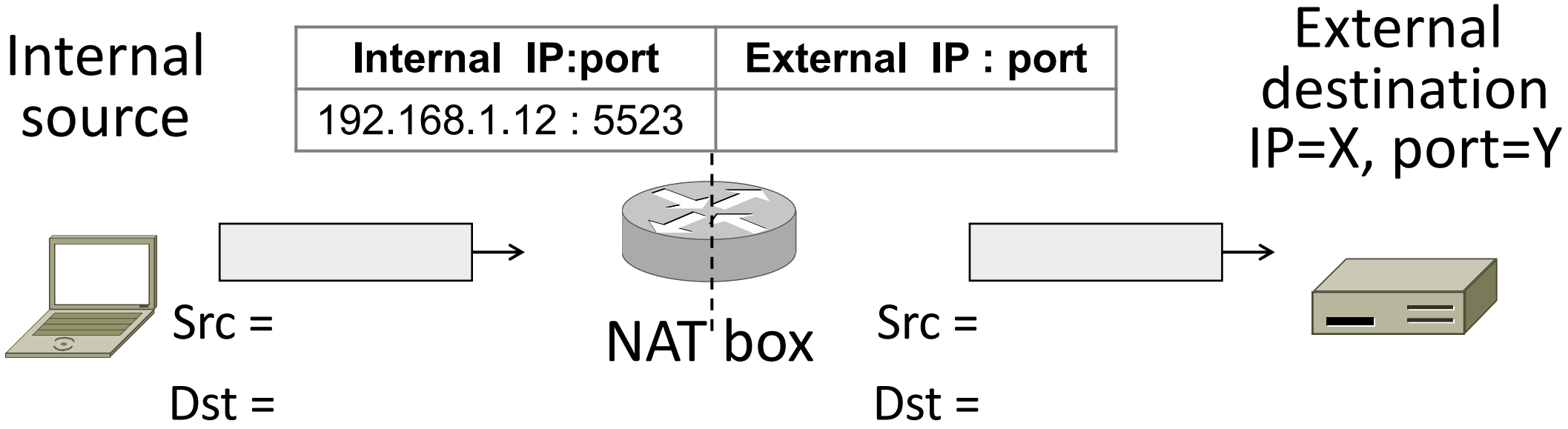
How NAT Works (3)

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



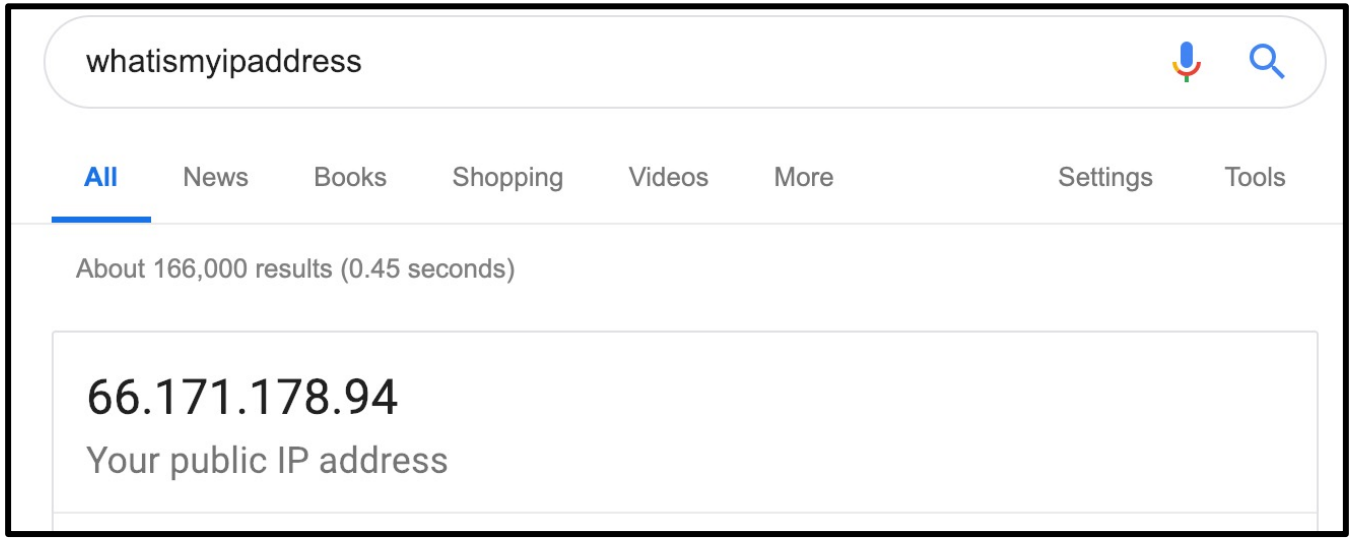
How NAT Works (4)

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



NAT in action

```
[Ratuls-MacBook-Pro:19wi ratul$ ifconfig en0
en0: flags=8863<UP,BROADCAST,SMART,RUNNING,SIMPLEX,MULTICAST> mtu 1500
        ether f0:18:98:a5:f9:cc
        inet6 fe80::440:e511:c06f:78f9%en0 prefixlen 64 secured scopeid 0xa
        inet 192.168.88.14 netmask 0xffffff00 broadcast 192.168.88.255
        nd6 options=201<PERFORMNUD,DAD>
        media: autoselect
        status: active
```



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)
- Doesn’t work if return traffic by passes the NAT
- Breaks apps that 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