

CSE 127 Computer Security

Stefan Savage, Fall 2025, Lecture 11

(change in plans)

Network Security I: background & basic attacks

Objectives today

Understand

- Architecture of the Internet protocol suite (TCP/IP)
CSE123 in 20mins
- Common weaknesses in basic networking protocols
- Available mitigations and their limitations

First: packets

A communications on the Internet is constructed of discrete, *self-addressed*, chunks of data: **packets**

- Apologies in advance, but networking has lots of words for packets when used in different contexts
 - Packet, frame, segment, datagram, cell

This is different from older circuit switched networks (e.g., the traditional phone system)

- Which set up **circuits** between two parties
- Then send signal (analog) or stream of bits (digital)

Review: Internet Protocol Suite

Application Layer

- Examples: SMTP, FTP, SSH, HTTP, etc.

Transport Layer: Port-addressed host-to-host communications (on LAN or WAN).

- User Datagram Protocol (UDP): single packet transmission with no reliability or ordering mechanisms.
- Transmission Control Protocol (TCP): connection establishment, reliable transmission, and flow-control.

Internet Layer (IP): Fragmentation, reassembly, and end-to-end (across network boundaries) routing of data packets.

- Provides a uniform interface that hides the underlying network topology.

Link Layer: Transmission of data frames within a local network (without intervening routers).

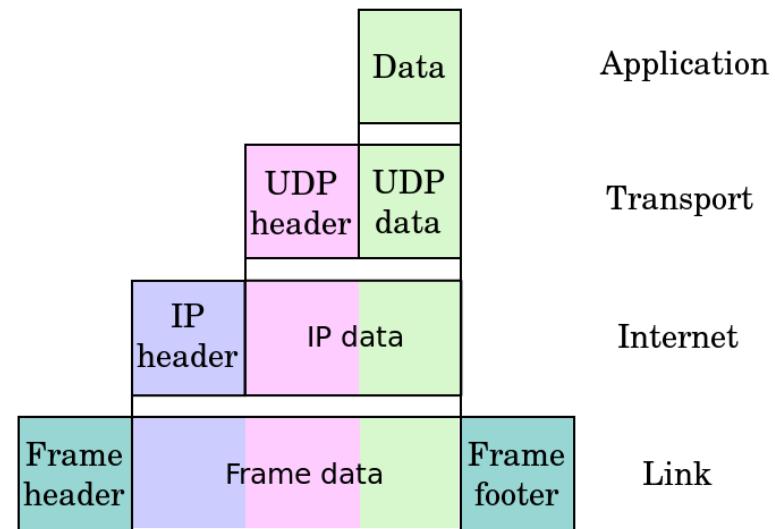
- Example: Ethernet

Physical Layer: Transmission of raw bits (rather than logical data packets) over a physical data link connecting network nodes.

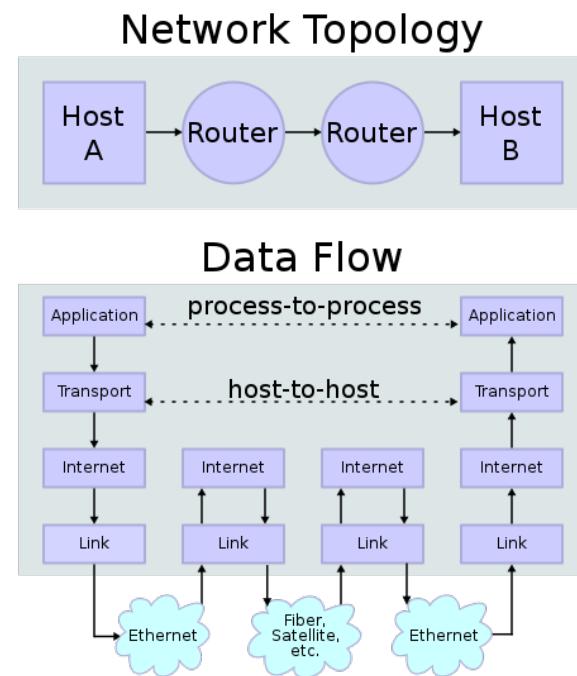
- Example: 1000BASE-T, 5Ghz WiFi
- [Technically not part of the Internet Protocol Model, but is still there]

Review: Internet Protocol Suite

Internet protocol suite	
Application layer	BGP · DHCP · DNS · FTP · HTTP · IMAP · LDAP · MGCP · MQTT · NNTP · NTP · POP · ONC/RPC · RTP · RTSP · RIP · SIP · SMTP · SNMP · SSH · Telnet · TLS/SSL · XMPP · more...
Transport layer	TCP · UDP · DCCP · SCTP · RSVP · more...
Internet layer	IP (IPv4 · IPv6) · ICMP · ICMPv6 · ECN · IGMP · IPsec · more...
Link layer	ARP · NDP · OSPF · Tunnels (L2TP) · PPP · MAC (Ethernet · DSL · ISDN · FDDI) · more...
V · T · E	



Review: Internet Protocol Suite



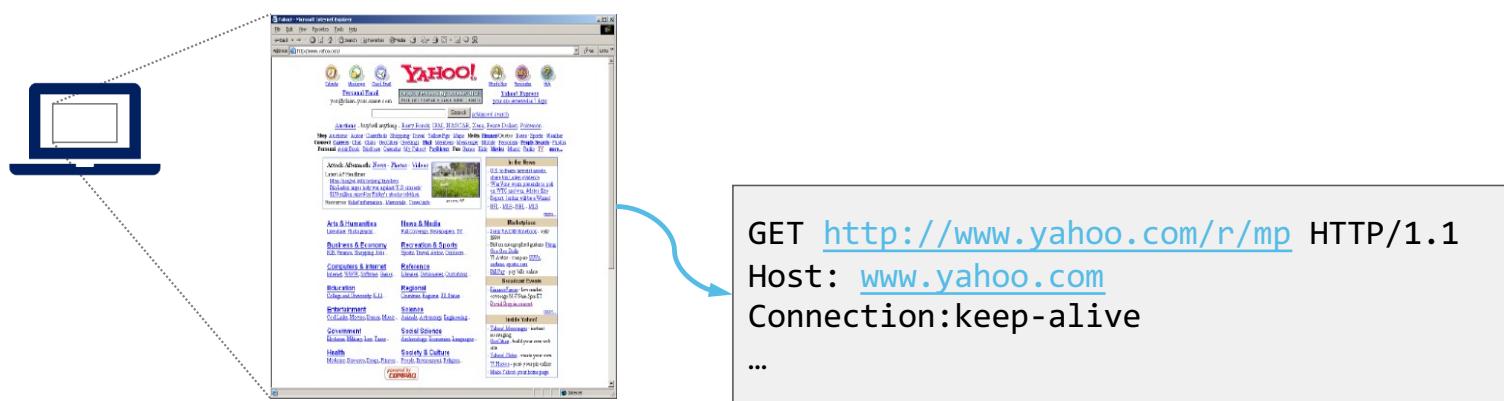
TCP/IP Protocol Stack by Example

ROUGHLY, what happens when I click on a URL while UCSD's network?



Application Layer (HTTP)

Turn click into HTTP GET request



Application Layer (Name Resolution)

Where is www.yahoo.com?

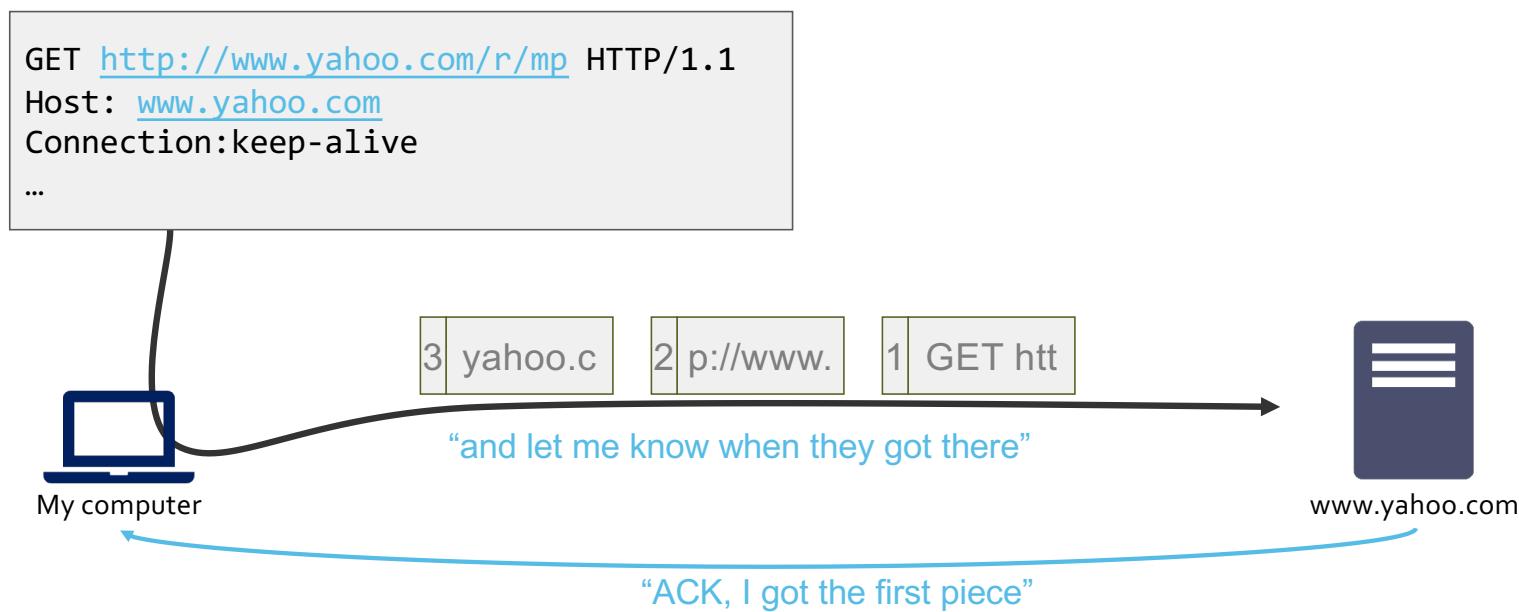


Ignore for now:
How did you know the address of the Local DNS server?
How did you send a message to it?
How did the Local DNS server know the answer?

Transport Layer (TCP)

Break message into pieces (TCP segments)

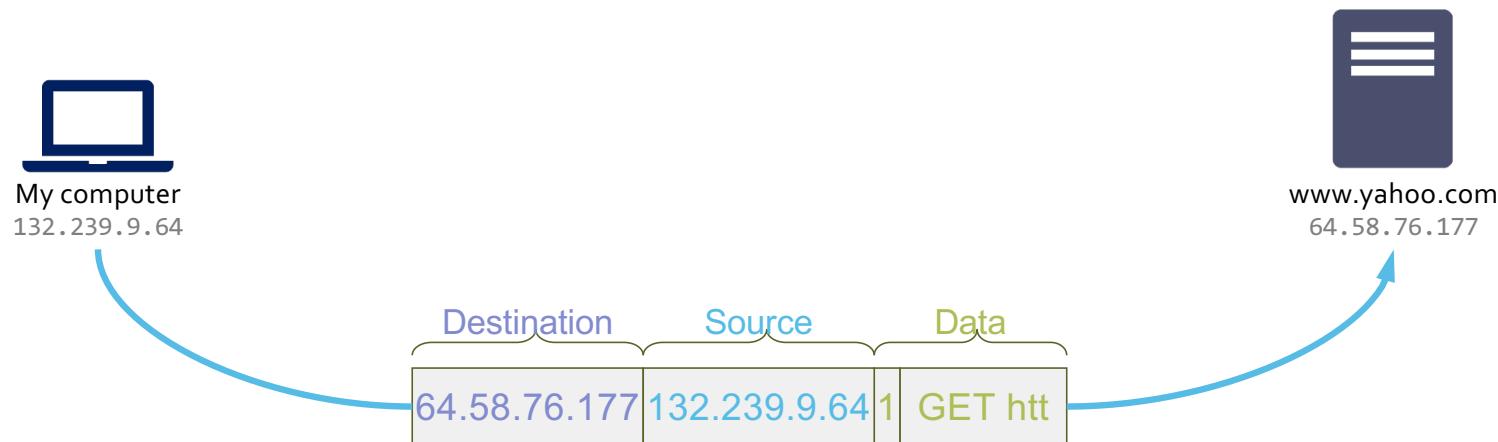
Should be delivered reliably & in-order



Network layer: IP Addressing

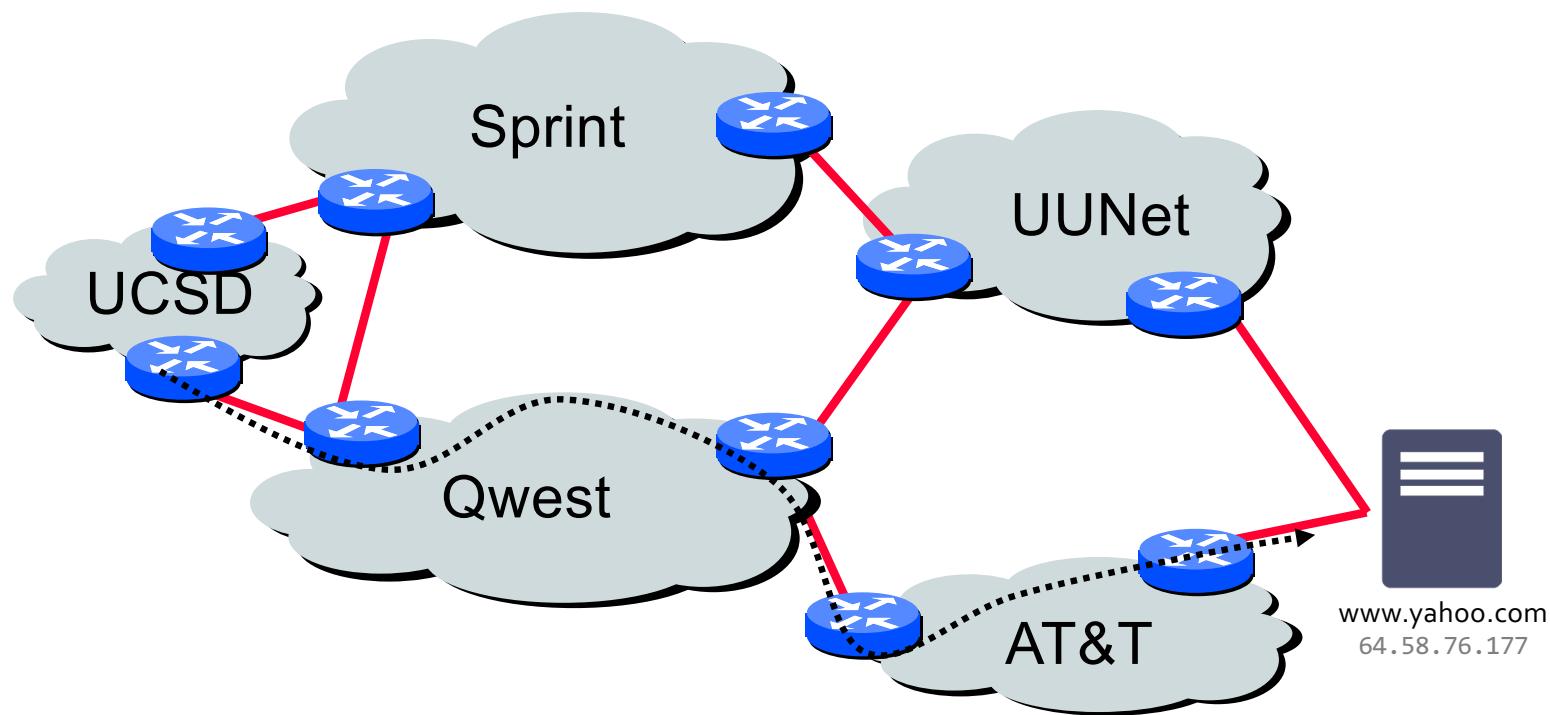
Address each packet so it can traverse network and arrive at host

Addresses are generally globally unique



Network Layer: IP Routing

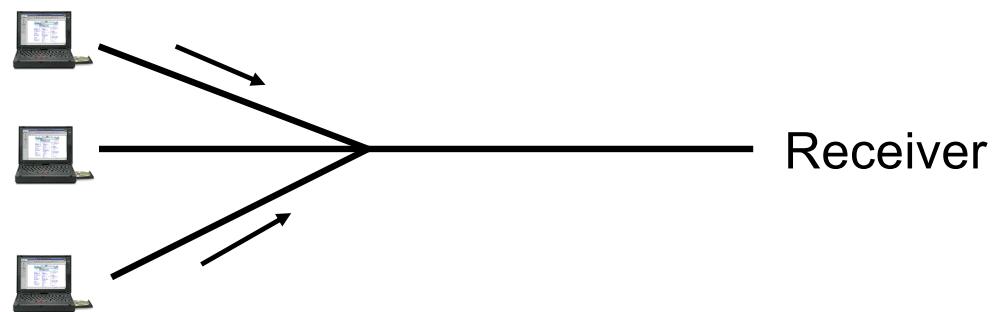
Each router forwards packet towards destination



Datalink layer (Ethernet)

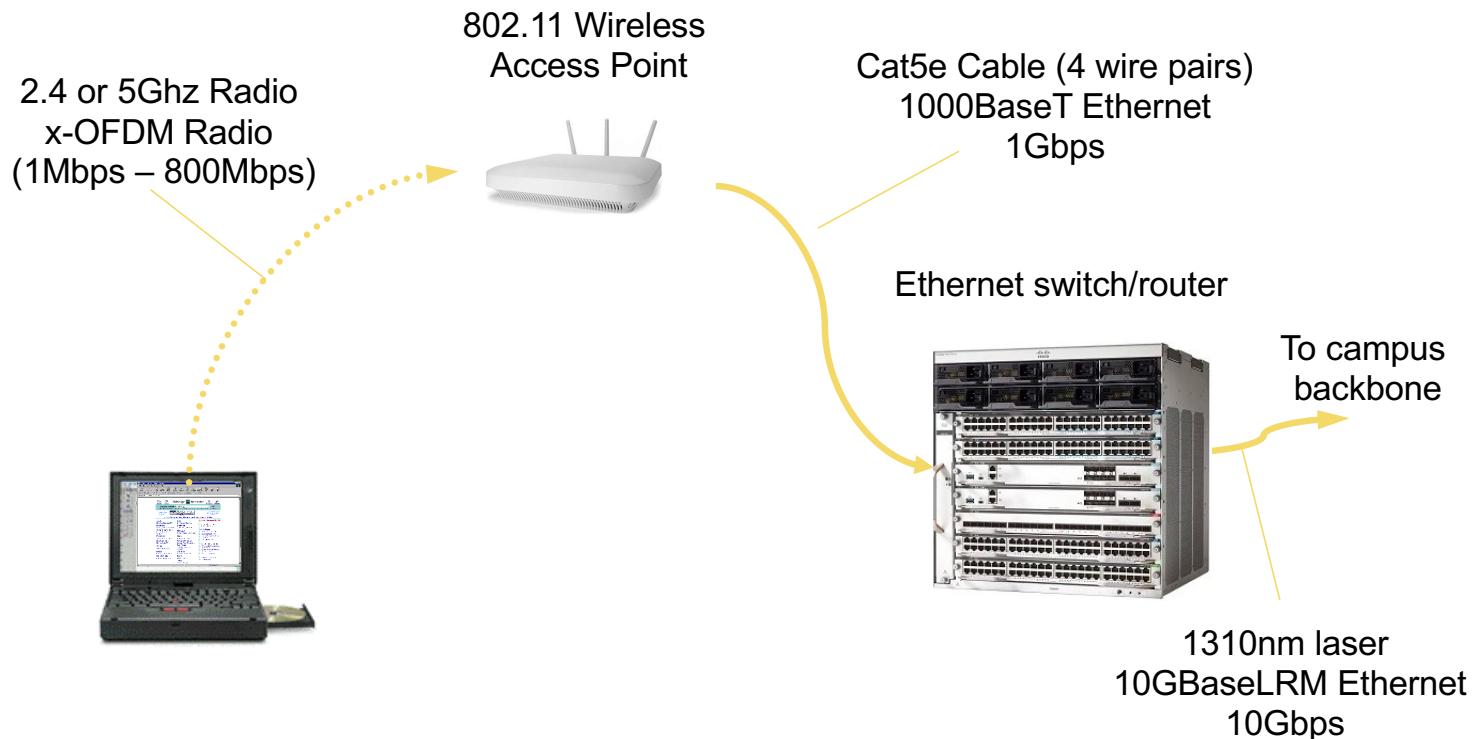
Media Access Control (MAC)

- Can I send now? Can I send now?



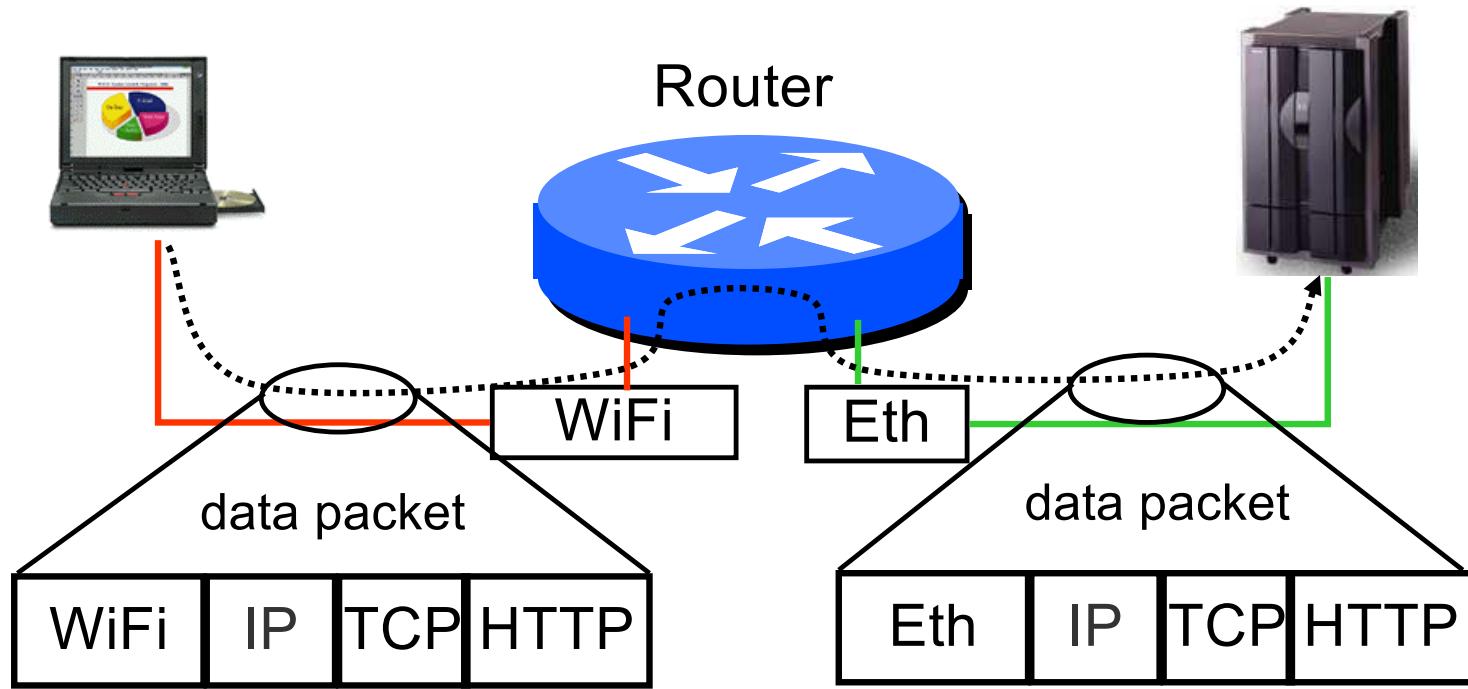
Send individual frames on a link

Physical layer



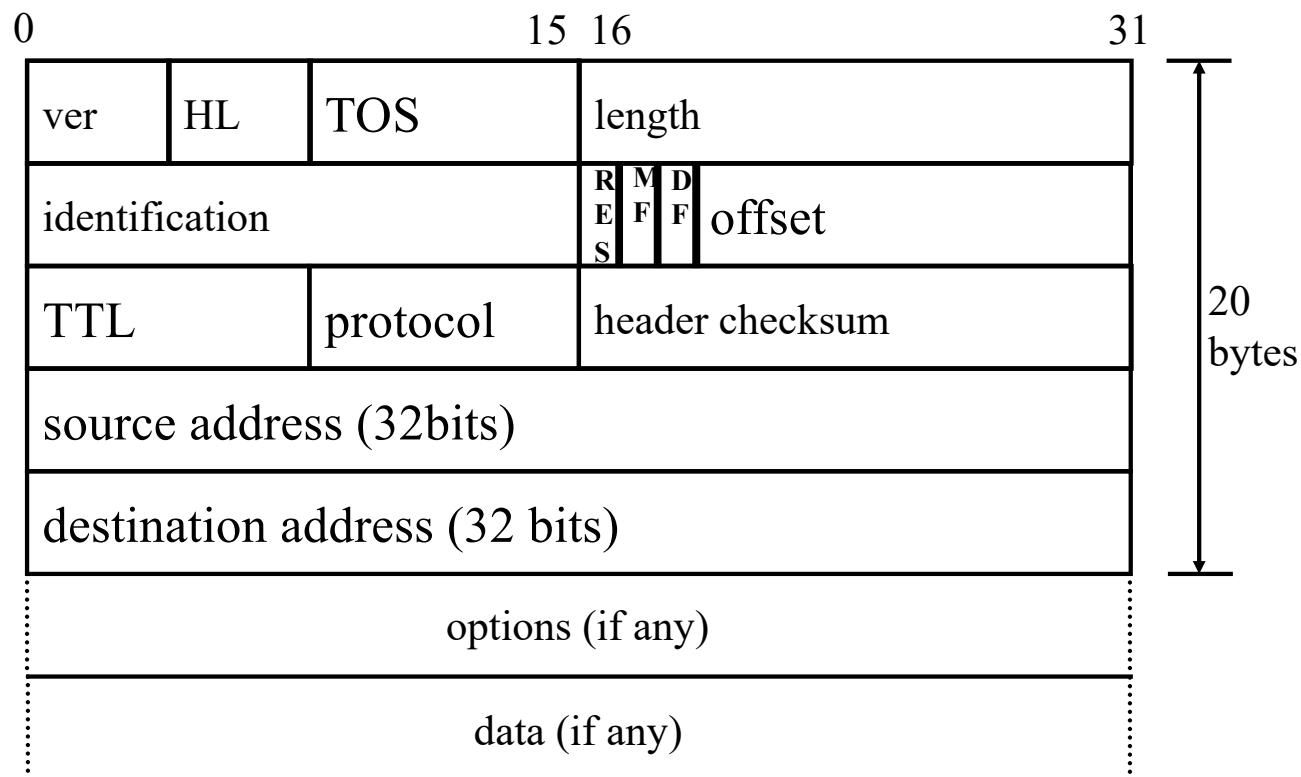
The value of the IP layer

Separate physical networks communicate to form a *single logical network* (IP addrs *globally unique**)



*except when
they aren't
(NAT, anycast)

IPv4 Packet Header



IP Protocol Functions (Summary)

Routing

- Your IP host knows location of the **local** router (gateway)
- IP gateway must know the routes to other networks (i.e., what is next hop?)
 - Packets usually take multiple hops to get to their destination
- Addresses are globally meaningful
 - 32 bits (IPv4), address separated into network part and host part (128bits w/IPv6)

Error reporting

- Send Internet Control Message Protocol (ICMP) packet back to source if there was a problem

Fragmentation and reassembly

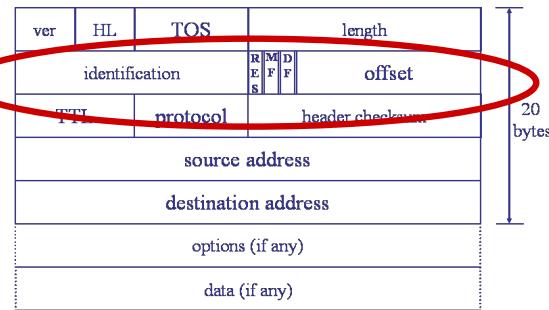
- If max-packet-size on next hop link < user-data-size in IP pkt

TTL field: decremented after every hop

- Packet dropped if TTL=0. Prevents infinite loops.

Fragmentation

- Sender writes **unique value** in *identification* field
- If router fragments packet it copies *this id* into each fragment
- *Offset* field indicates position of fragment in bytes (offset 0 is first)
 - *MoreFragments* flag indicates that this isn't the last fragment
 - *DontFragment* flag tells gateway not to fragment
- All routers must support 576 byte IPv4 packets (MTU)



IP Fragmentation and Reassembly

	length =4000	ID =x	MF =0	offset =0	
--	-----------------	----------	----------	--------------	--

One large datagram becomes
several smaller datagrams

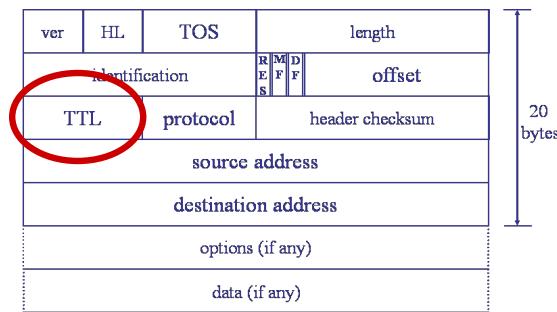
	length =1500	ID =x	MF =1	offset =0	
--	-----------------	----------	----------	--------------	--

	length =1500	ID =x	MF =1	offset =1480	
--	-----------------	----------	----------	-----------------	--

	length =1040	ID =x	MF =0	offset =2960	
--	-----------------	----------	----------	-----------------	--

TTL (Time-to-Live)

- How many more routers can this packet pass through?
 - ◆ Designed to limit packet from looping forever
- Each router decrements TTL field
- If TTL is 0 then router discards packet



TCP Primer

TCP provides reliable, ordered delivery of bytes

Establishes a stateful bi-directional session between two IP:port endpoints

- Port represents an application endpoint on a host (e.g., port 80 for a Web server)

Each side maintains:

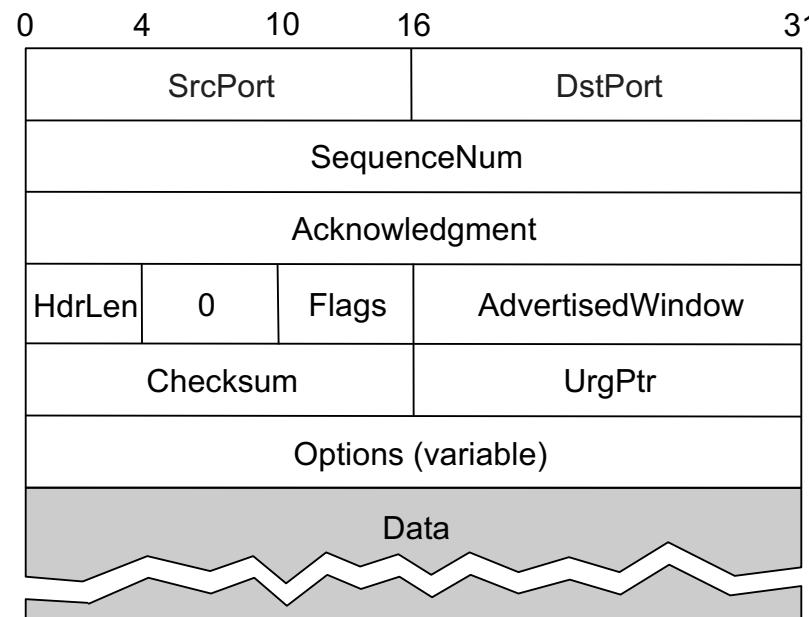
- Sequence number: sequence base (i.e., *start from here*) + count of bytes sent
- Acknowledgement number: acknowledgement base + count of bytes received

Special packet flags

- SYN: I want to start a connection
- FIN: I want to shut down a connection
- RST: We are killing this connection now

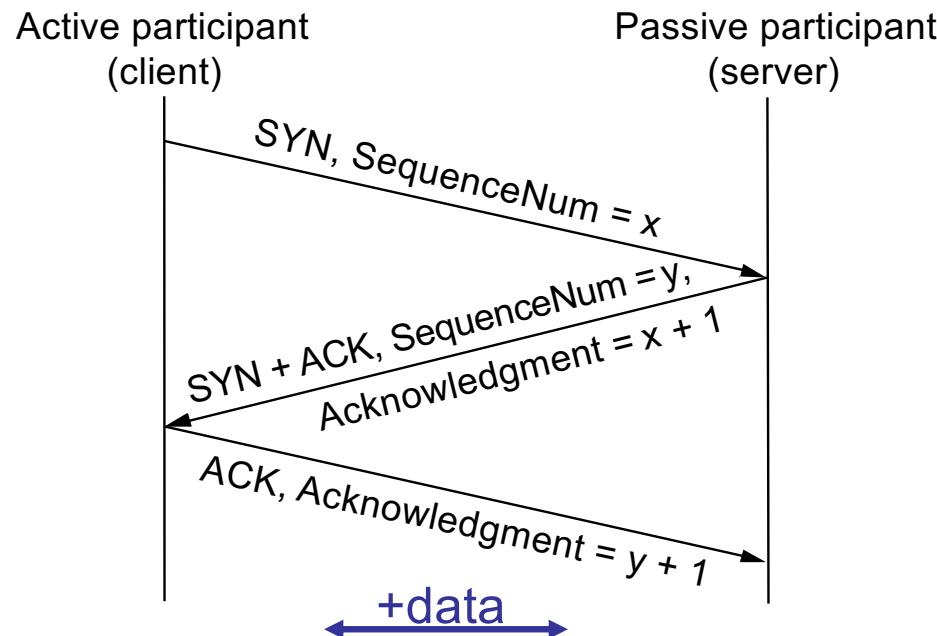
TCP Header Format

- **Ports** plus IP addresses identify a connection



Connection Setup: Agree on initial Sequence #'s

- Three-way handshake



TCP/IP Security (1970's)

Original TCP/IP design: Trusted network and hosts

- Administered by mutually trusted parties

End-to-end Principle

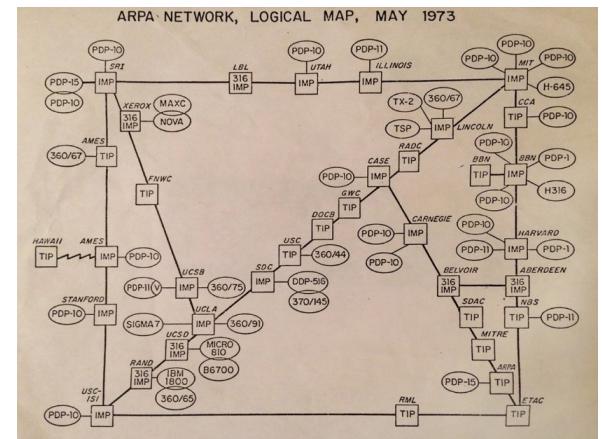
- Intelligence is at the edges
 - Network is simple

Optimized for speed and simplicity, maintains no state

Robustness Principle

- “In general, an implementation must be **conservative** in its sending behavior, and **liberal** in its receiving behavior. That is, it must be careful to send well-formed datagrams, but must accept any datagram that it can interpret (e.g., not object to technical errors where the meaning is still clear).”

<https://www.ietf.org/rfc/rfc0791.txt>



<https://en.wikipedia.org/wiki/ARPANET>

TCP/IP Security

Built-in trust assumptions:

- Network protocols used only as intended
 - Correct packet headers
 - Consideration of others' resources
 - Rate limiting of costly operations
- Hosts controlled by trusted administrators
 - Random people can't get onto the network
 - Correct information reported by hosts
 - Protocols implemented correctly

TCP/IP Security (1980's)

Wait ... what if we can't trust everyone?

- *"When describing such attacks, our basic assumption is that the attacker has more or less complete control over some machine connected to the Internet. This may be due to flaws in that machine's own protection mechanisms, or it may be because that machine is a microcomputer, and inherently unprotected. Indeed, **the attacker may even be a rogue system administrator.**"*

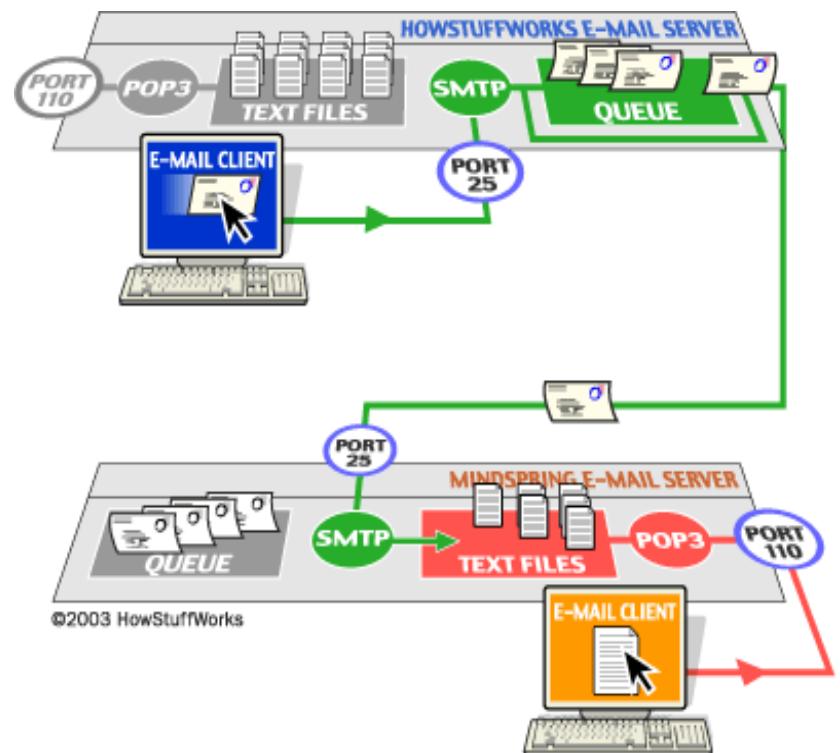
Security Problems in the TCP/IP Protocol Suite, Steve Bellovin 1989

1980s threat model

- Can't trust the hosts
 - Compromised hosts
 - Untrusted insiders on internal networks
 - Anyone can connect to public Internet
- But **network** is still trusted

Aside: we also trust application layer Example - how e-mail works in practice

```
Connected to mx1.mindspring.com
220 mx1 - SMTP ready
he1o test
250 mx1.mindspring.com
Hello abc.sample.com [220.57.69.37], pleased to meet you
mail from: test@sample.com
250 2.1.0 test@sample.com... Sender ok
rcpt to: jsmith@mindspring.com
250 2.1.5 jsmith... Recipient ok
data
354 Enter mail, end with "." on a line by itself
from: test@sample.com
to: jsmith@mindspring.com
subject: testing
John, I am testing...
.
250 2.0.0 e1NMajH24604 Message accepted for delivery
quit
221 2.0.0 mx1.mindspring.com closing connection
Connection closed by foreign host.
```



TCP/IP Security (today)

Can't trust the network either

- Network equipment can be compromised
- Untrusted network operators
- Anyone can access the physical channel of wireless networks

Recall: Attacker Models

Person in the middle: can see, block, and modify traffic

- E.g., attacker controls wifi access point

Passive: Eavesdrop on traffic

- E.g., attacker has passive tap or recorded traces

Off-path: attacker can inject traffic into network

- Anyone with access to network

No Confidentiality

Who can see the packets you send?

- Network (routers, switches, access points, etc.)
- Unprotected WiFi network: everyone within range
 - WPA/WPA2 Personal (PSK): everyone on same network
- Non-switched (i.e. old school) Ethernet: everyone on same network
- Switched Ethernet: everyone gets their own link, but... sometimes someone can intercept your traffic (a few slides from now)

No Authentication

TCP/IP offers no authentication of packets

- Source address in IP header is set by sender

Attacker with direct access to network (including PitM) can spoof source address

- Spoof: forge, set to arbitrary value

Connectionless protocols (UDP) especially vulnerable

Some consequences:

- Can **blast packets at a target** and, by using spoofed source addresses, make it look like someone else is attacking them (denial-of-service)
- Can try to interfere with existing communications between hosts (e.g., by injecting packets purporting to be part of that communication)
- Can't count on source address for authentication (but we still do... e.g., UCSD Library)

Link Layer interception

Physical channel is often shared by multiple hosts on the local network.

- Examples: open WiFi, non-switched Ethernet

Link layer controls access to the physical medium.

- Also known as the Media Access Control (MAC) layer.
- Apologies: acronym collision – not the same as Message Authentication Code (MAC)

How to make sure each host only gets frames addressed to it?

Each host is responsible for picking up frames addressed to it and ignoring the others.

- Honor system!

Filtering typically happens on the network card (or equivalent).

- Only frames addressed to this host are parsed and passed on to the layer above.

Many support “promiscuous” mode – all frames are picked up.

But you can intercept in other ways too...

Host configuration

Address binding (IP to MAC)

Routing

Network Routing

Say I want to send packet to 8.8.8.8 ...

Step 1: Is destination on local network?

- Check subnet masks of local networks

Status: **Connected**

Ethernet 1 is currently active and has the IP address 132.239.17.19.

Configure IPv4:

Manually

IP Address:

132.239.17.19

Subnet Mask:

255.255.255.0

Router:

132.239.17.1

DNS Server:

132.239.0.252, 128.54.16.2, 8.8.8.8

Search Domains:

ucsd.edu

802.1X:

WPA: UCSD-P...

Connect

Network Routing

Say I want to send packet to 8.8.8.8 ...

Step 1: Is host on local network?

- Local?: send directly
- Not local?: send via *default gateway* (aka the router)

Status: **Connected**

Ethernet 1 is currently active and has the IP address 132.239.17.19.

Configure IPv4: **Manually**

IP Address: 132.239.17.19

Subnet Mask: 255.255.255.0

Router: 132.239.17.1

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Search Domains: ucsd.edu

802.1X: WPA: UCSD-P...

Connect

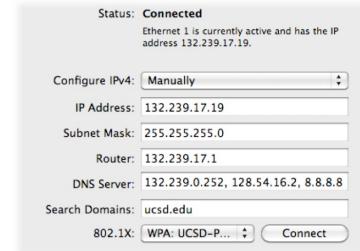
Wait a second...

How do I know all this stuff?

- The address of the router, my own IP address, the netmask, the address of the DNS server, etc

Dynamic Host Configuration Protocol (DHCP)

- Automatically configures each new host attached to network
- Basic idea
 - Host broadcasts “DHCP discover” on local network (special broadcast address)
 - DHCP server responds with information for your host (IP addr, gateway, etc)
- What if someone listens for DHCP requests and sends answer?
 - Can tell someone to use the router of their choosing (and DNS server)
 - One ad hoc defense, **dhcp snooping**: network switch configured to block DHCP messages from non-trusted hosts that aren’t known to be DHCP servers



Network Routing

Say I want to send packet to 8.8.8.8 ...

Step 1: Is host on local network?

- Local?: send directly
- Not local?: send via default gateway

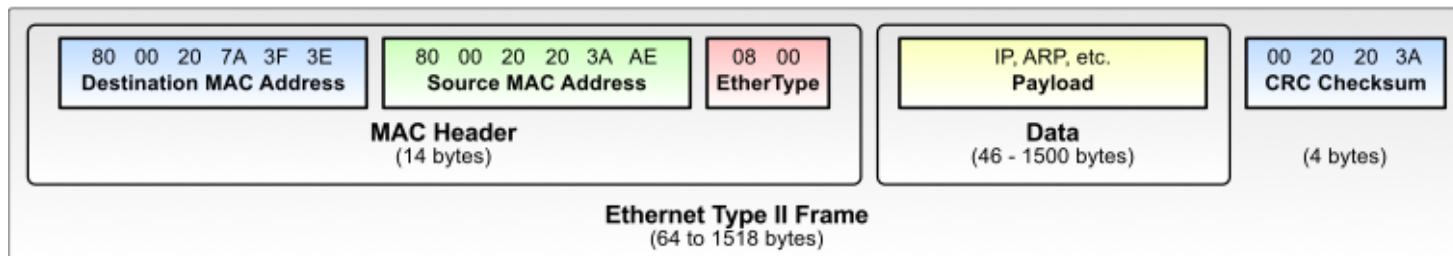
Step 2: Create IP packet

Step 3: Create and send link layer (e.g. Ethernet) frame

- 48 bit source address, 48 bit destination address

Network Routing

Ethernet frame:



Host needs to fill in Ethernet destination address

- MAC address of host on local network
- MAC address of gateway for host not on local network

How to find Ethernet address from an IP address?

Address Resolution Protocol (ARP)

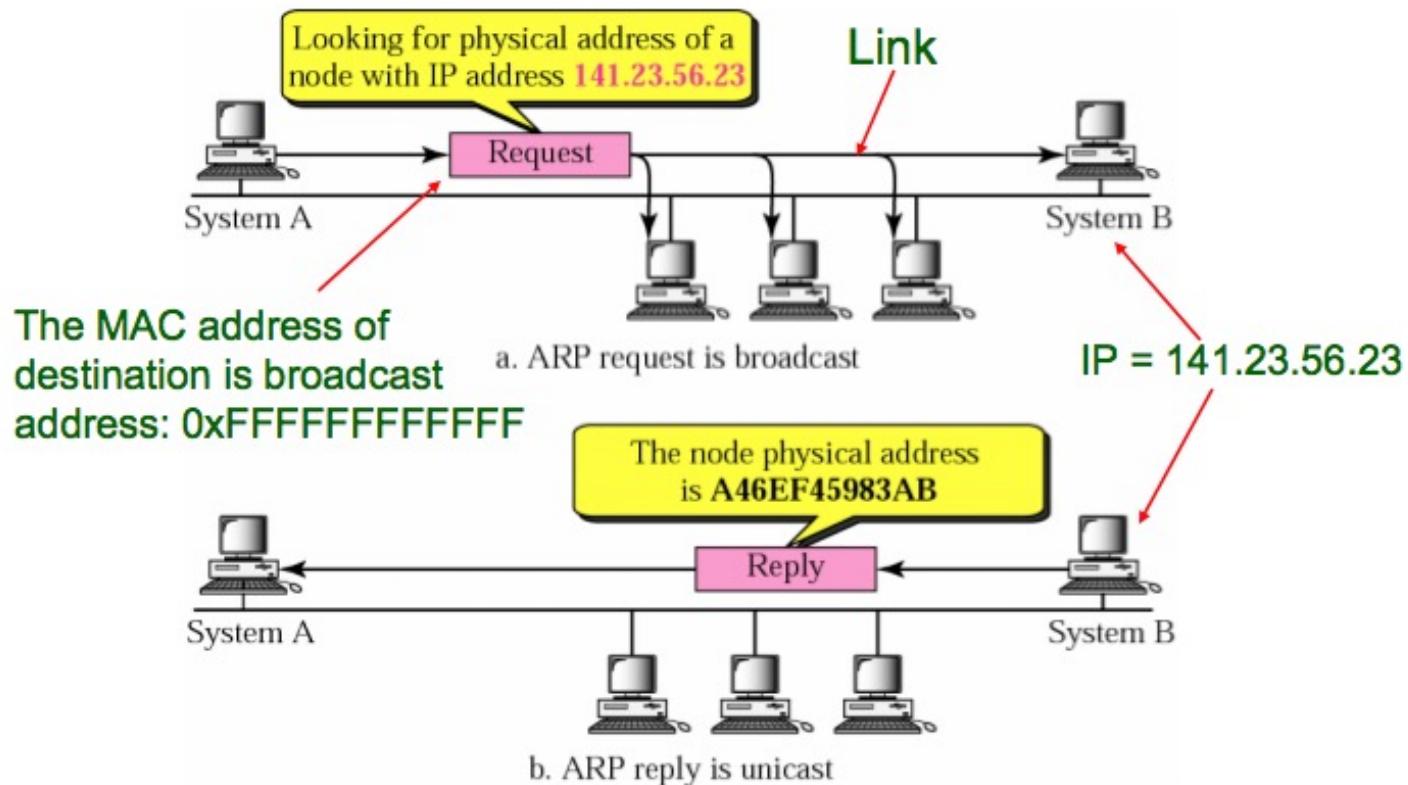
Address Resolution Protocol (ARP)

- used to query hosts on local network to get link-layer address for an IP address

Protocol sketch

- Alice (looking for Bob's IP) **broadcasts** an ARP request:
"What is the MAC address of `10.0.0.3`?"
- Bob sees broadcast (asking about his IP address) and replies:
"The MAC address of `10.0.0.3` is `01:02:03:04:05:06`."
- Alice sends IP packet for `10.0.0.3` in an Ethernet frame to `01:02:03:04:05:06`.

Address Resolution Protocol (ARP)



Address Resolution Protocol (ARP)

ARP messages are link-layer frames (e.g. Ethernet/WiFi)

ARP requests are broadcast (on the local subnet)

Anyone can send an ARP reply

ARP Spoofing

Since

- ARP requests are broadcast (on the local subnet)
- Anyone can send an ARP reply

Attacker on the network can impersonate any other host

- Who has the MAC address for IP address 8.8.8.8?
- "Uh... I do... send your traffic to me..." (ARP proxying)

Mitigation

- **Static** ARP tables
 - Impractical for all but small fixed networks
- "Port binding" on switch
 - Restrict MAC and IP addresses allowed to a single port on a switch at a time; first mover wins
 - Might not work well for WiFi... why not?
- Depend on higher level host authentication to save you
 - E.g. SSH or TLS

Problems With Addressing

This problem repeats at every protocol layer:

- Source needs to send something to destination
- How to know which address corresponds to name?

Domain name to IP address

IP routing

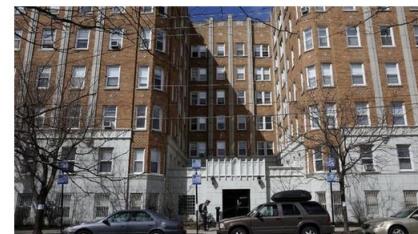
IP address to Ethernet address

...



The image shows the header of the Chicago Tribune website. It features a dark blue header bar with the "Chicago Tribune" logo in white. To the left are "SECTIONS" and a search icon. To the right are "SUBSCRIBE" (with a "SALE: 10¢ a week" offer), "LOG IN", and a weather widget showing "94°". Below the header, a navigation bar includes links for "SPORTS", "BREAKING", "MOST POPULAR", "OPINION", "ENTERTAINMENT", and "BUSINESS".

Change-of-address scam moved UPS corporate headquarters to tiny Rogers Park apartment, feds say



A Rogers Park man is under investigation after postal inspectors say they uncovered a scheme to scam Atlanta-based UPS out of mail and checks through the use of a change-of-address form that redirected the mail to the man's Ashland Avenue apartment on the Far North Side. (Nancy Stone / Chicago Tribune)

By Jason Meisner · Contact Reporter
Chicago Tribune

APRIL 23, 2018, 5:00 AM

Network Routing

Say I want to send packet to 8.8.8.8 ...

Step 1: Is host on local network?

- Local?: send directly
- Not local?: send via default gateway

Step 2: Create IP packet

Step 3: Create and send link layer (e.g. Ethernet) frame

Step 4: Gateway picks next router in path and forwards the IP packet

- Repeat until destination is reached
- How to know which router to forward to next?

Border Gateway Protocol (BGP)

Border Gateway Protocol (BGP) is used to manage IP routing information between networks on the Internet

Each BGP node maintains connections to a set of trusted neighbors

- Connections between neighbors may be (weakly) authenticated

Neighbors share routing information

- I can reach network X directly, I can reach network Y via ISP Z, I can...

No authorization

- Malicious (or malfunctioning) BGP nodes may provide incorrect routing information that redirects IP traffic

BGP Hijacking (just two examples)

2008 Pakistan tried to block YouTube within the country

- Pakistan Telecom claimed ownership of YouTube's IP block via BGP
- BGP nodes forwarded this routing information
- YouTube is "sinkholed" globally
- <https://www.ripe.net/publications/news/industry-developments/youtube-hijacking-a-ripe-ncc-ris-case-study>

2018 MyEtherWallet.com compromised, \$100,000's reported stolen

- Attackers used BGP hijacking to claim ownership of a chunk of Amazon Route 53 (DNS) addresses
- Used hijacked DNS traffic to direct MyEtherWallet.com-bound traffic to attackers' servers in Russia
- <https://dyn.com/blog/bgp-hijack-of-amazon-dns-to-steal-crypto-currency/>

IP Spoofing Attacks

There is no authentication in Link or Internet layers

Even if routing is correct, Eve can still spoof Alice's IP address

- Eve can send IP packets claiming to be from Alice
- Eve may not be able to receive IP packets addressed to Alice

UDP: trivial

- Stateless protocol, each datagram is independent of others

TCP: more complicated, but still possible

- Two endpoints maintain a shared state
- Attacker must be able to guess it

TCP Connection Spoofing

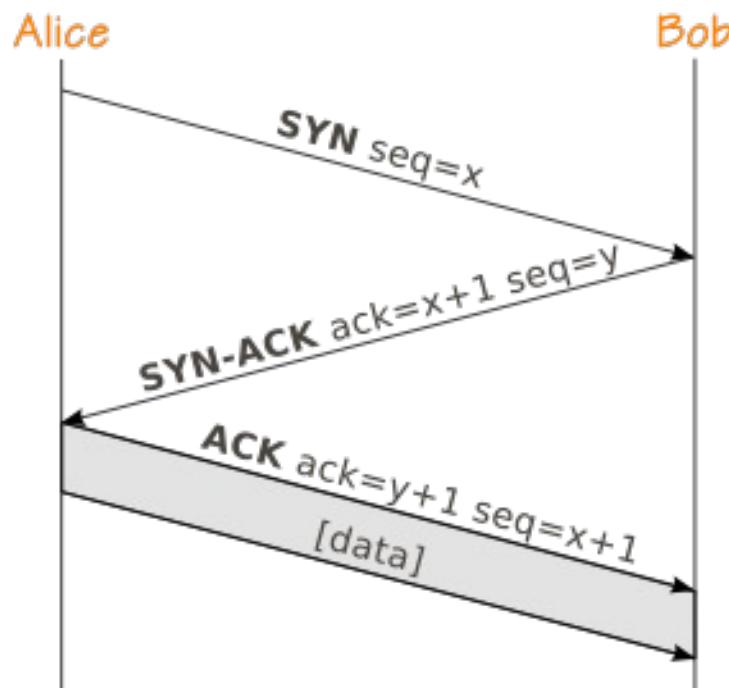
Eve needs to complete the TCP three-way handshake between "Alice" and Bob

Eve can't see traffic between Alice and Bob

- "TCP off-path attack"

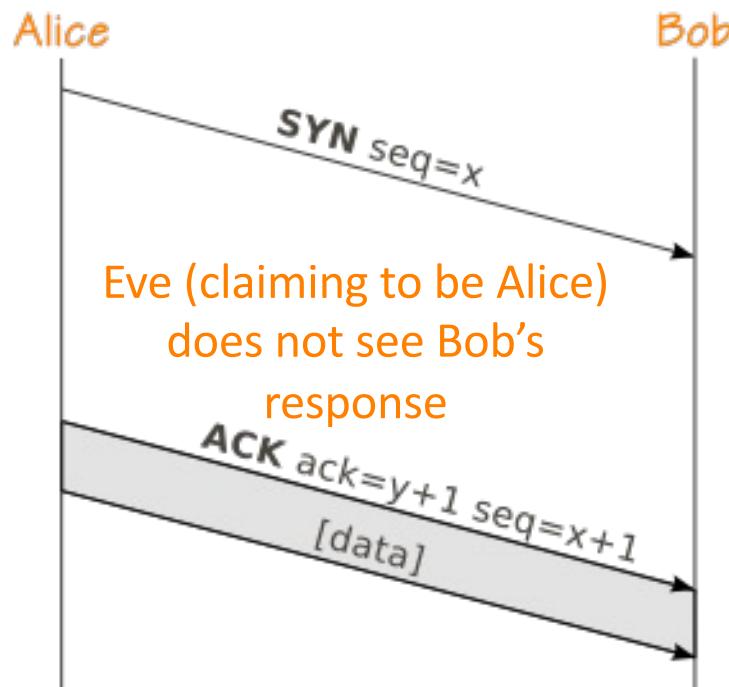
Eve needs to guess initial sequence number y in order to correctly ACK Bob's SYN

Recall: Three-Way Handshake



source: Wikipedia

Eve's Three-Way Handshake problem



source: Wikipedia

TCP Connection Spoofing

The sequence number field is 32 bits

Early implementations just incremented a global counter used to initialize sequence numbers (ISN) for TCP connections

- RFC 793 requires counter incrementing every $4 \mu\text{s}$ (250 kHz)
- Early BSD Unix kernels incremented by a large constant every second
- Attack: Eve could talk to Bob directly get an ISN, then spoof a SYN from Alice and estimate what ISN he was likely to offer her

Later pseudo-random number generators were used

- Still global, weaknesses in PRNGs allowed guessing
 - Watch series of ISNs to try to infer current PRNG sequence and guess next ISN
- We now use cryptographically strong random number generators for picking initial sequence numbers

Related issue: Blind port scanning

Context: attackers would like to know what TCP services are offered on a particular host (so it knows how to attack them)

Port scan:

- Send TCP SYN to each port number on the host
- See if you get a SYN/ACK back (there is a service at that port number) or a RST (there is nothing there)

Problem

- You expose your source address when doing this
- Attackers would like to be able to do it anonymously...

Related issue: Blind port scanning

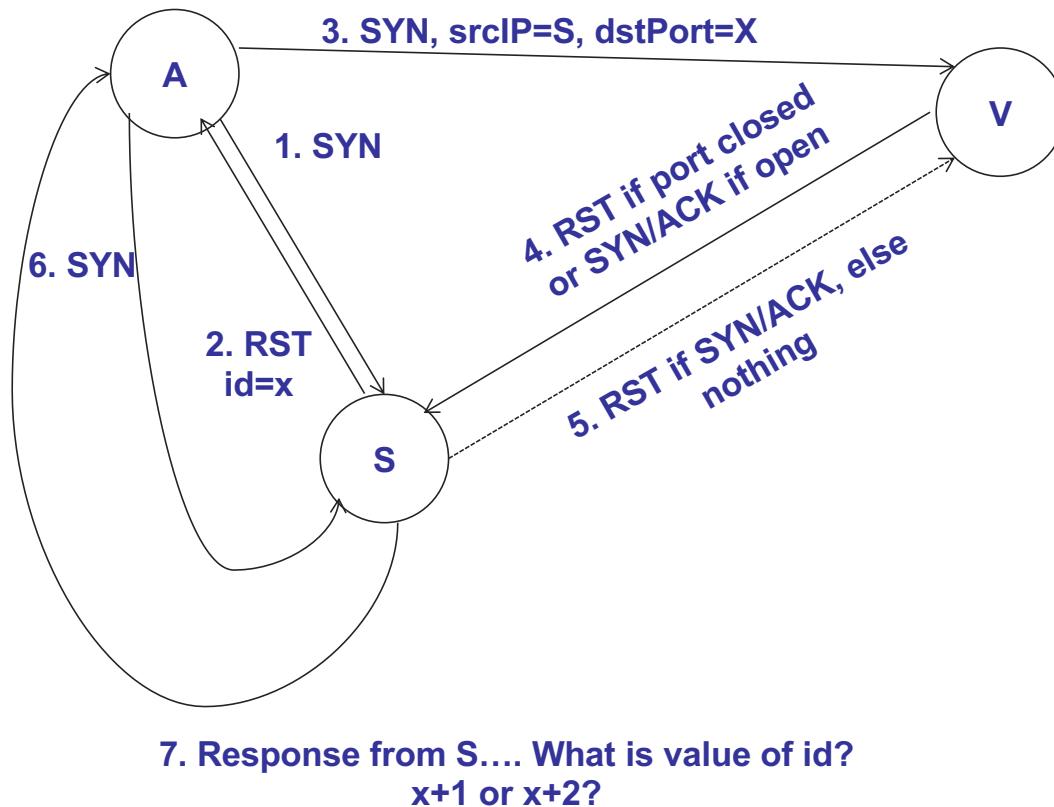
Key trick: exploiting *IP identification* field in the IP header

- Recall the IP identification field was used for fragmentation
- Hosts need to ensure that it is unique across packets have outstanding
- An super easy way to do this is to use a global counter on the host (increment after you send each packet)

If host A sends a pkt with id=5, then next pkt will have id=6, followed by id=7, etc

So if you **receive** a pkt from host A at time t_1 with id =**10**, and another packet at time t_2 with id=**12**, you can *infer*... that host A sent another packet somewhere between t_1 and t_2

Blind port scanning



Additional Resources

Wireshark

- <https://www.wireshark.org/>

Attacking Network Protocols

- By James Forshaw
- <https://nostarch.com/networkprotocols>

