Internet Protocol Security

CS155 Computer and Network Security

Stanford University

What is the Internet?

Global network that lets hosts communicate

Internet provides best-effort delivery of ***packets*** between hosts

Packet: a structured sequence of bytes

- **Header:** metadata used by network
- **Payload:** user data to be transported

Packets are forwarded by routers from sender to destination host

Internet Protocol (IP)

Internet Protocol (IP) defines what packets that cross the Internet need to look like to be processed by routers

Every host is assigned a unique identifier (“IP Address”)

Every packet has an IP header that indicates its sender and receiver

Routers forward packet along to *try* to get it to the destination host

Rest of the packet should be ignored by the router

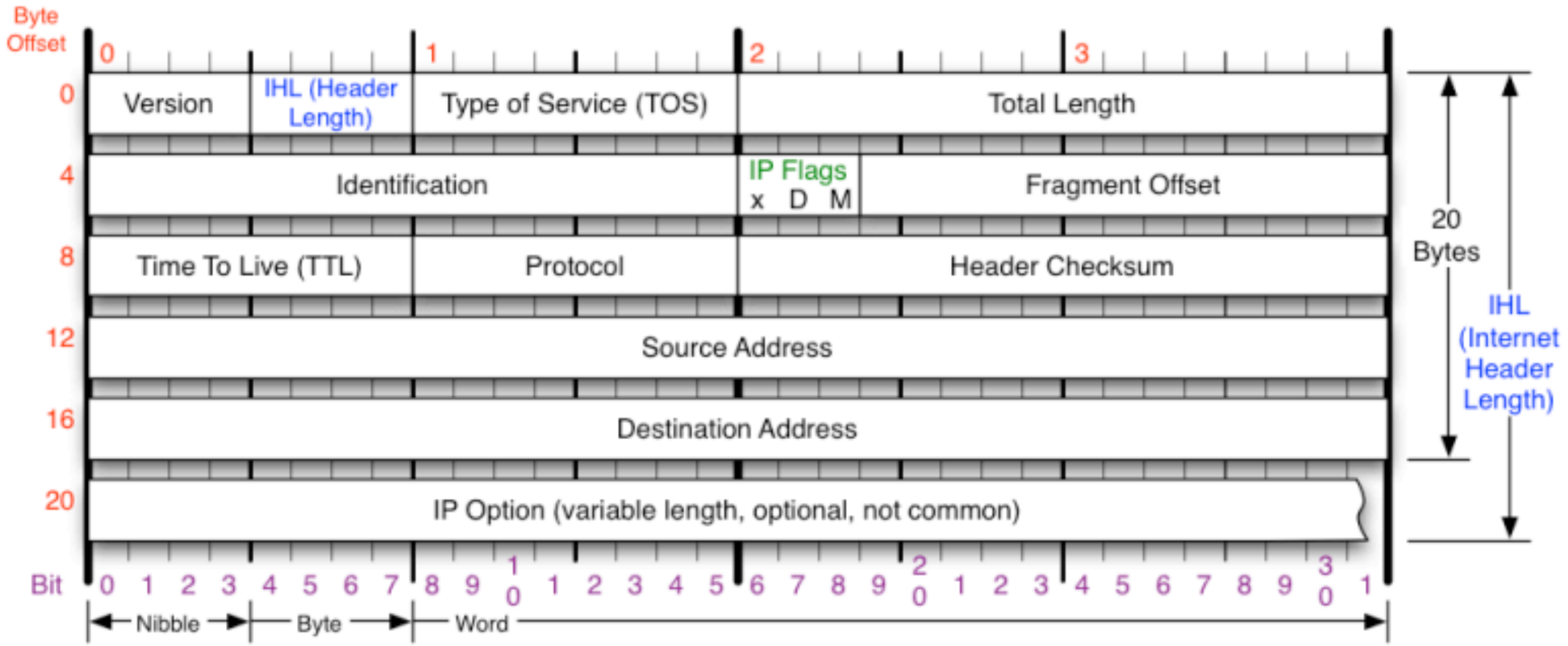
IP Addresses

IPv4: 32-bit host addresses
  Written as 4 bytes in form A.B.C.D
    where A,...,D are 8 bit integers in decimal
    (called *dotted quad*) *e.g.* 192.168.1.1

IPv6: 128 bit host addresses
  Written as 16 bytes in form AA:BB::XX:YY:ZZ
    where AA,...,ZZ are 16 bit integers in hexadecimal
    and :: implies zero bytes
    e.g. 2620:0:e00:b::53 = 2620:0:e00:b:0:0:0:53

IPv4 Header

Instruct routers and hosts what to do with a packet
All values are filled in by the sending host



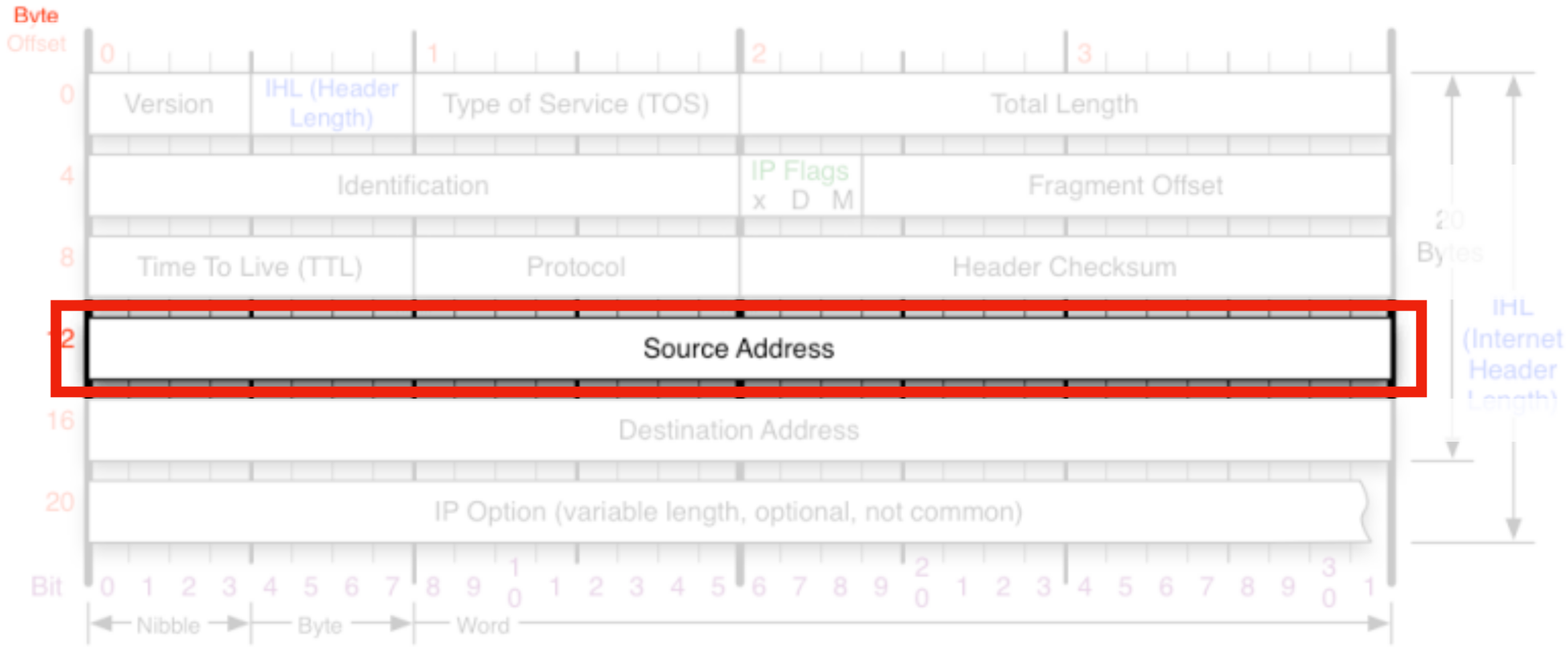
Destination Address

Sender sets destination address

Routers try to forward packet to that address

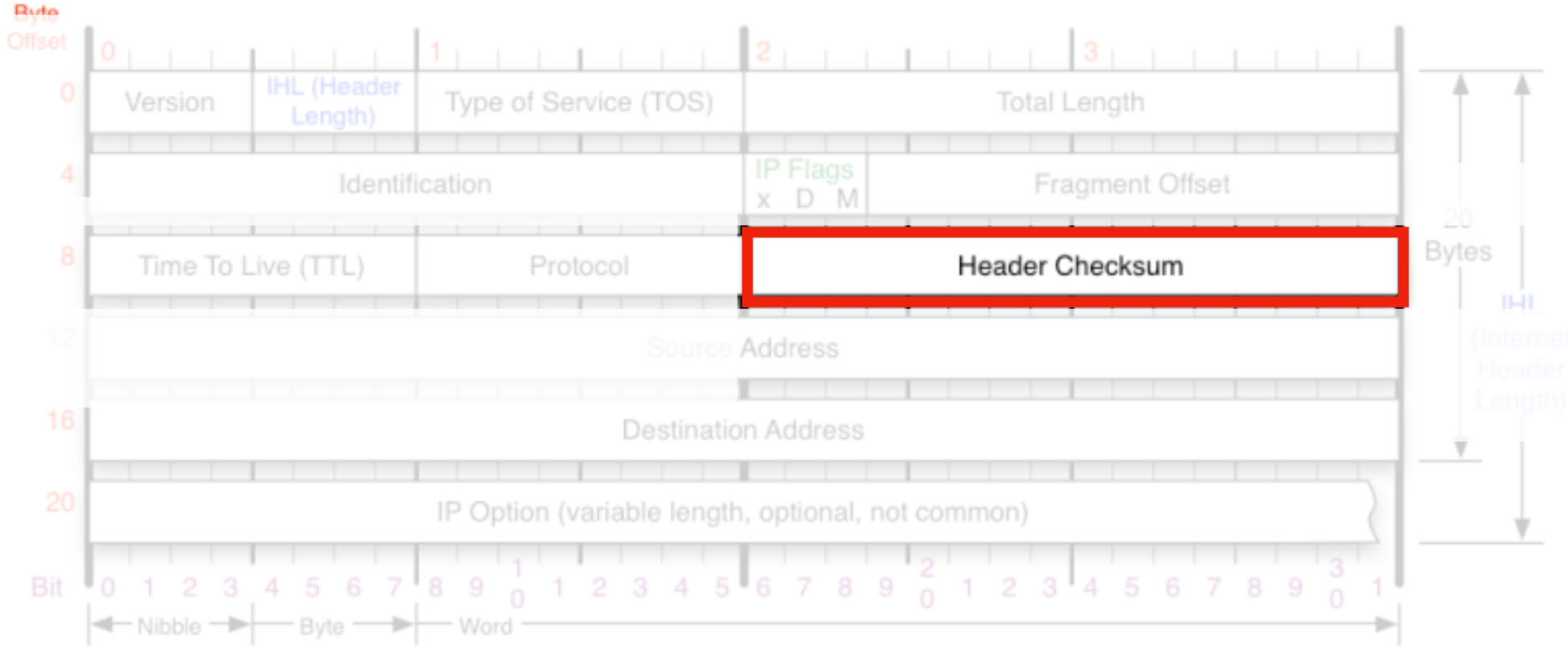
Source Address

Source Address (sender)
Sender fills in. Routers due not verify.



Checksum

16-bit Simple Header checksum (filled in by sender)



IP Security

Client is trusted to embed correct source IP

- Easy to override using lower level network sockets
- **Libnet:** a library for formatting raw packets with arbitrary IP headers

Anyone who owns their machine can send packets with arbitrary source IP

- Denial of Service Attacks
- Anonymous infection (if one packet)

Internet Protocol (IP)

Yes:

Routing. If host knows IP of destination host, route packet to it.

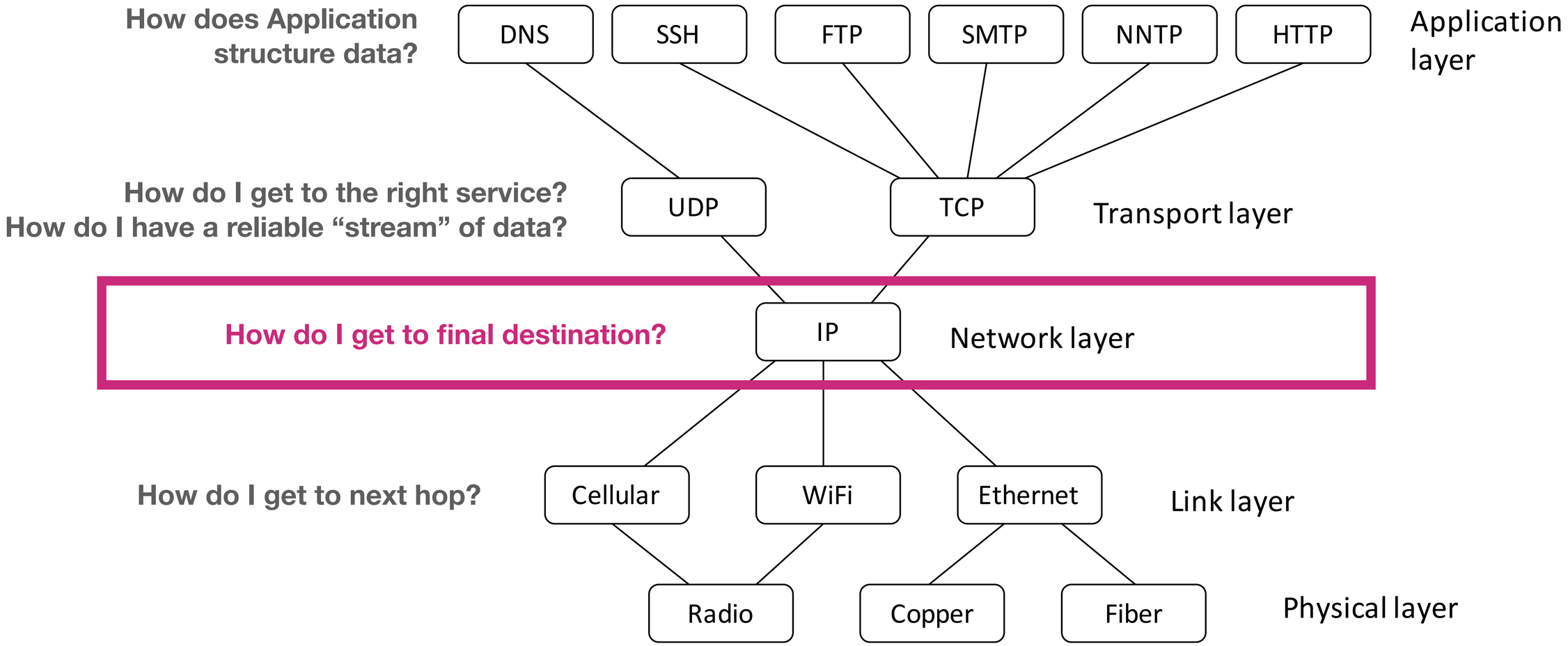
Fragmentation and reassembly: Split data into packets and reassemble

Error Reporting: (maybe, if you're lucky) tell source it dropped your packet

No:

Everything else. No ordering. No retransmission. No (real) error checking. No acknowledgement of receipt. No "connections". No security. Just packets.

Protocol Layering



Protocol Layering

Networks use a stack of layers

Lower layers provide services to layers above

Don’t care what higher layers do

Higher layers use services of layers below

Don’t care how lower layers implement services

Layers define abstraction boundaries

At a given layer, all layers above and below are opaque

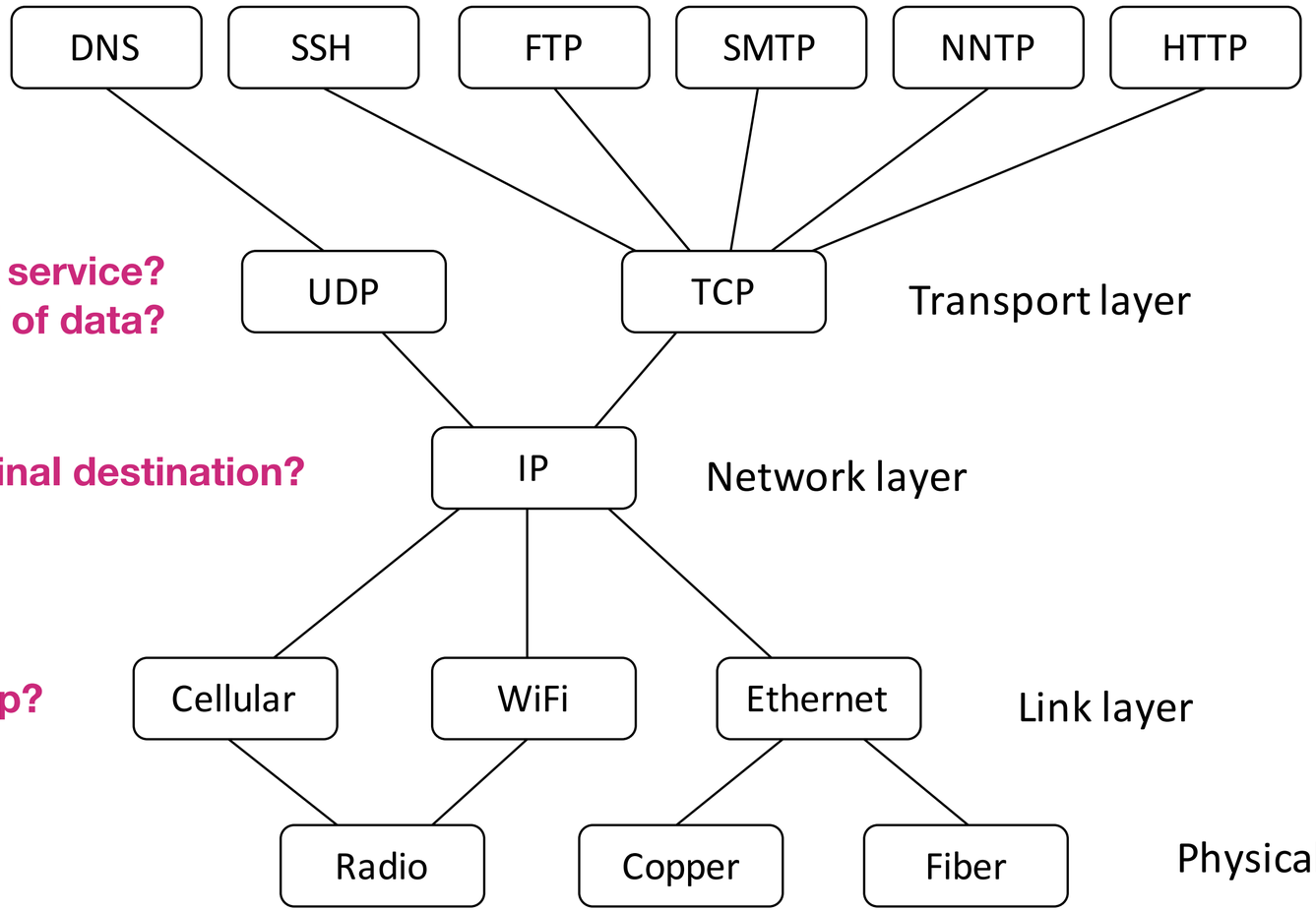
Protocol Layering

How does Application structure data?

How do I get to the right service?
How do I have a reliable “stream” of data?

How do I get to final destination?

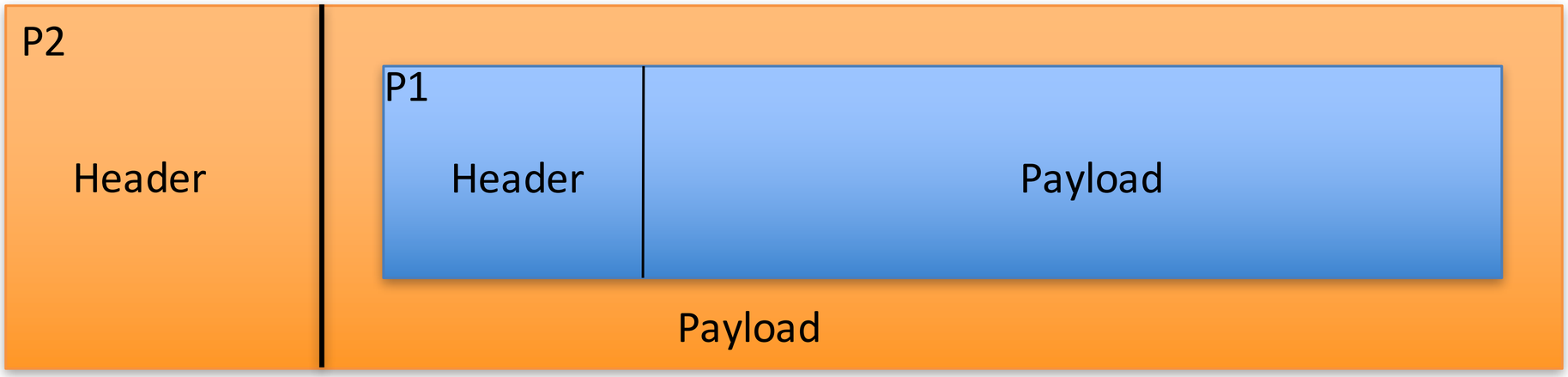
How do I get to next hop?



Packet Encapsulation

Protocol N1 can use the services of lower layer protocol N2

- A packet P1 of N1 is encapsulated into a packet P2 of N2
- The payload of p2 is p1
- The control information of p2 is derived from that of p1



Link Layer

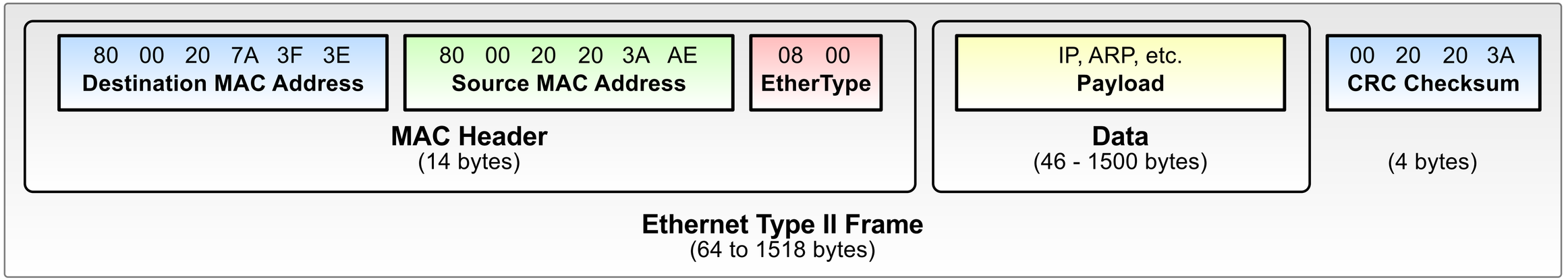
Model assumed that hosts can deliver and accept packets from Internet routers

In practice, hosts not connected directly to router

Link layer provides connectivity between hosts and routers

Ethernet

Most common Link Layer Protocol. Let's you send packets to other local hosts.



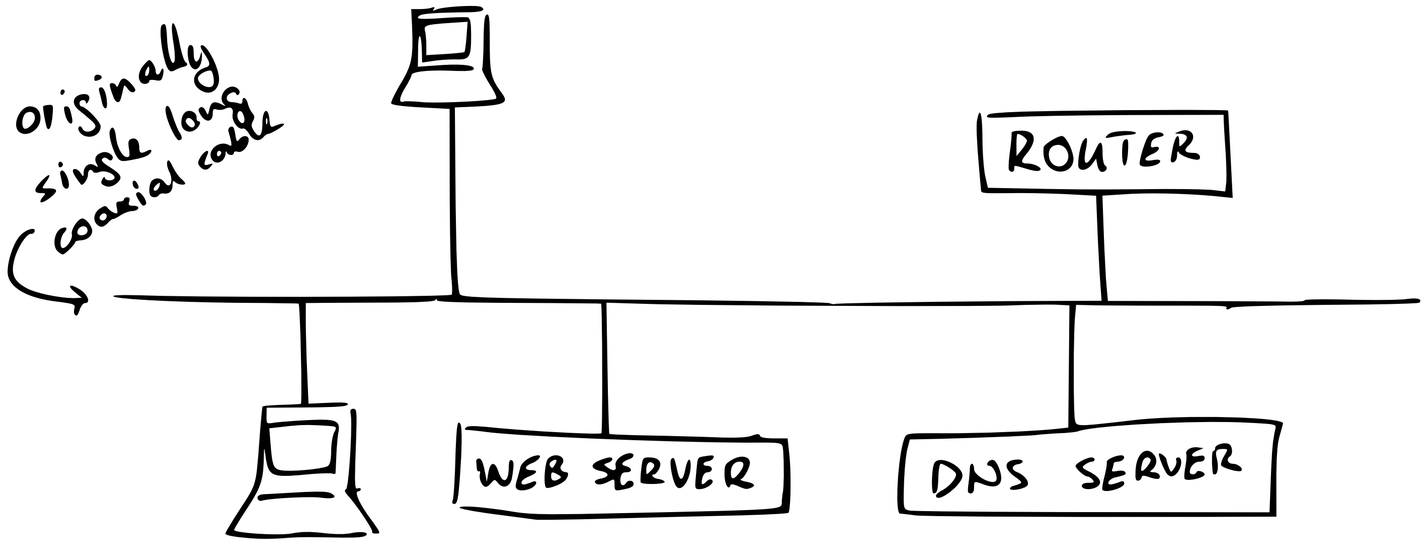
At layer 2 (link layer) packets are called *frames*

MAC addresses: 6 bytes, universally unique

EtherType gives layer 3 protocol in payload
- 0x0800: IPv4
- 0x0806: ARP
- 0x86DD: IPv6

Ethernet

Originally broadcast. Every local computer got every packet.



Switched Ethernet

With switched Ethernet, the switch *learns* at which physical port each MAC address lives based on MAC source addresses

If switch knows MAC address M is at port P,
it will only send a packet for M out port P

If switch does not know which port MAC address M lives at, will broadcast to all ports

Ethernet

```
[zakir@scratch-01:~$ ifconfig
ens160: flags=4163<UP,BROADCAST,RUNNING,MULTICAST>  mtu 1500
        inet 10.216.2.64  netmask 255.255.192.0  broadcast 10.216.63.255
        inet6 fe80::250:56ff:fe86:b203  prefixlen 64  scopeid 0x20<link>
        ether 00:50:56:86:b2:03  txqueuelen 1000  (Ethernet)
        RX packets 1404151714  bytes 1784388363701 (1.7 TB)
        RX errors 0  dropped 73  overruns 0  frame 0
        TX packets 1155689210  bytes 6010503085464 (6.0 TB)
        TX errors 0  dropped 0 overruns 0  carrier 0  collisions 0
```

Two Problems

Local: How does a host know what MAC address their destination has?

Internet: How does each router know where to send each packet next?

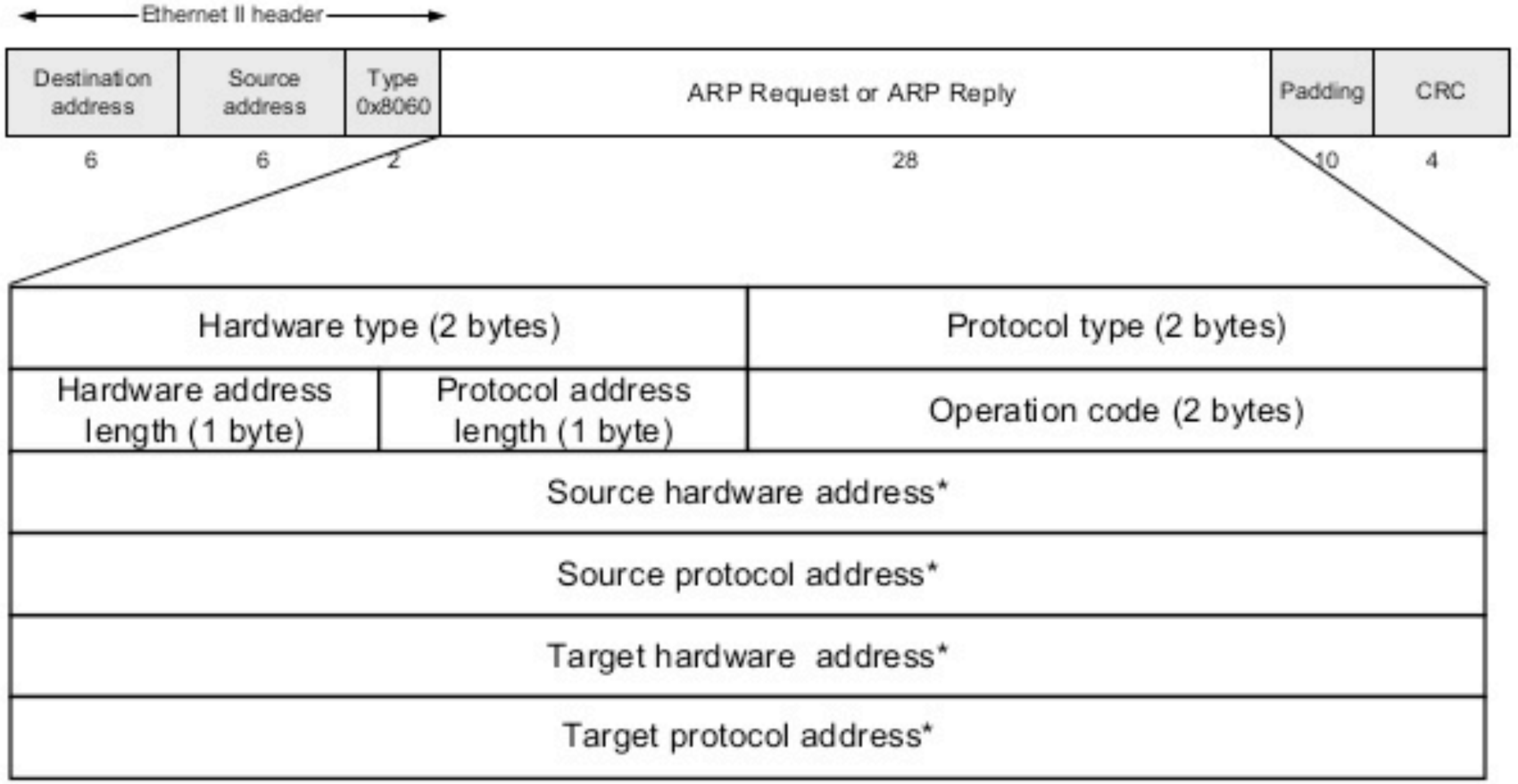
ARP: Address Resolution Protocol

ARP is a Network protocol that lets hosts map IP addresses to MAC addresses

Host who needs MAC address M corresponding to IP address N broadcasts an ARP packet to LAN asking, “who has IP address N?”

Host that has IP address N will reply, “IP *N* is at MAC address *M*.”

ARP Packet



* Note: The length of the address fields is determined by the corresponding address length fields

ARP Security

Any host on the LAN can send ARP requests and replies: *any host can claim to be another host on the local network!*

- This is called *ARP spoofing*

This allows any host X to force IP traffic between any two other hosts A and B to flow through X *(MitM!)*

- Claim N_A is at attacker's MAC address M_X
- Claim N_B is at attacker's MAC address M_X
- Re-send traffic addressed to N_A to M_A, and vice versa

Routing (BGP)

BGP (Border Gateway Protocol): protocol that allows routers to exchange information about their routing tables

Each router announces what it can route to all of its neighbors.

Every router maintains a global table of routes

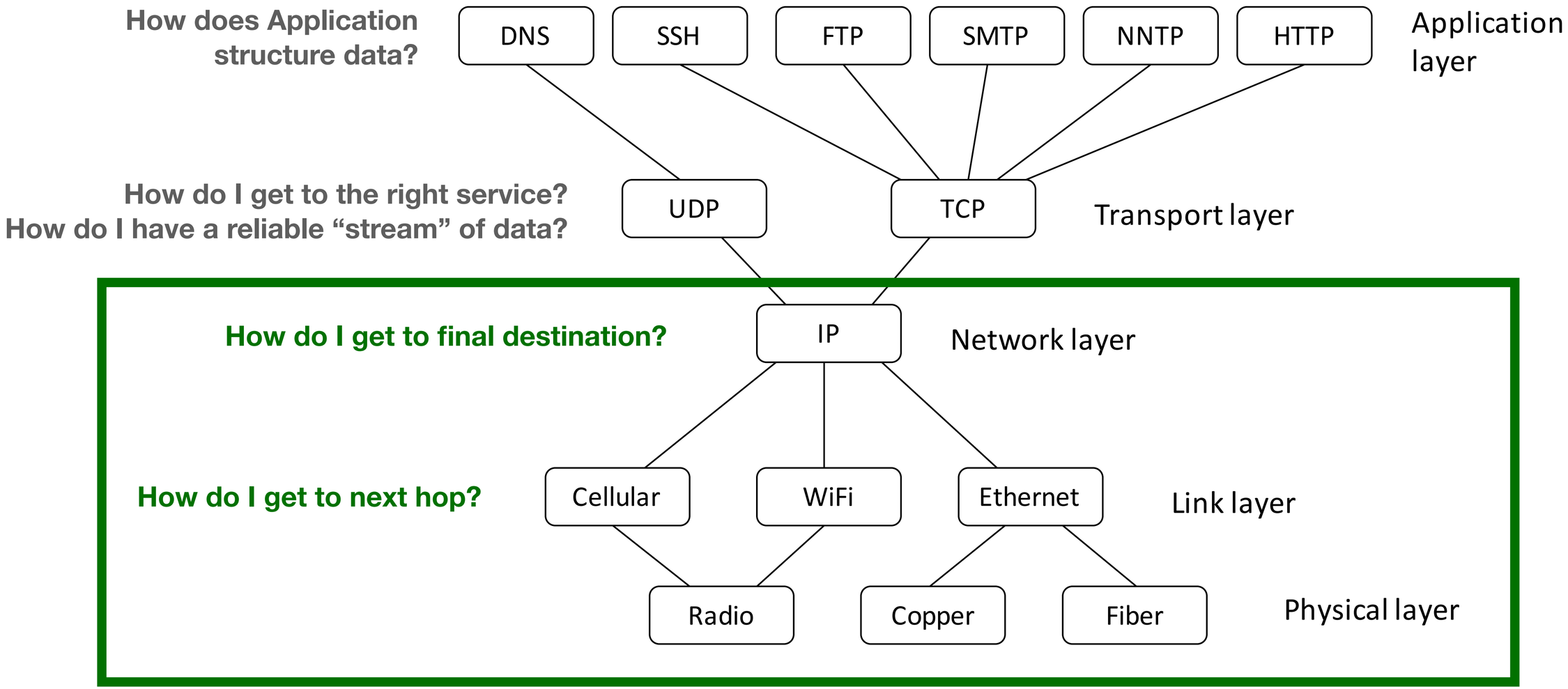
Pakistan hijacks YouTube

On 24 February 2008, Pakistan Telecom (AS 17557) began advertising a small part of YouTube's (AS 36561) assigned network

PCCW (3491) did not validate Pakistan Telecom's (17557) advertisement for 208.65.153.0/24

Youtube offline.

Protocol Layering



From Packets to Streams

Most Internet applications want a data stream abstraction (not best-effort packets)

Application on host X wants to send a sequence of bytes to application on host Y. Wants reliable, in-order delivery of data

Transmission Control Protocol (TCP) *provides* a data stream abstraction *using* a best-effort packet transport (IP)

Transmission Control Protocol

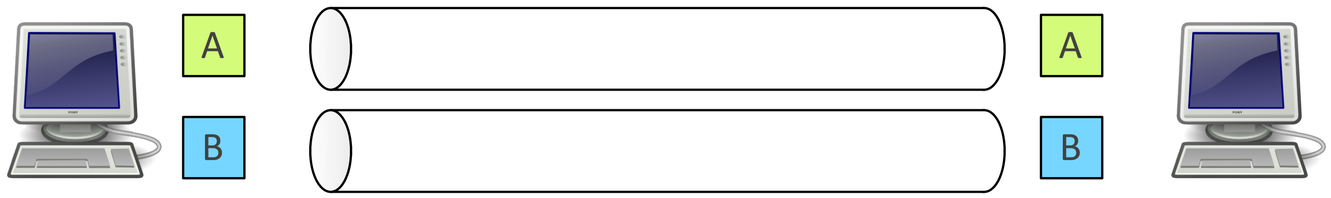
Have: network that will deliver packets

Packets may be dropped, re-ordered, duplicated

Want:

Abstraction of a stream of bytes between *applications* on different hosts

Bytes delivered reliably and in-order

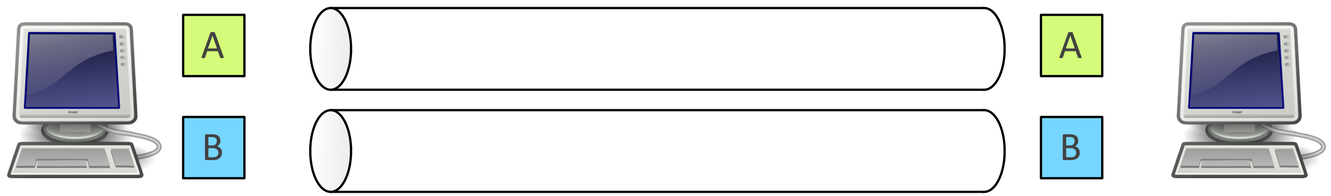


Ports

Each application is identified by a *port number*

TCP connection established between port *A* on host *X* to port *B* on host *Y*
Ports are 1–65535 (16 bits)

Some destination port numbers used for specific applications by convention



Ports

Port	Application
80	HTTP (Web)
443	HTTPS (Web)
25	SMTP (mail)
67	DHCP (host config)
22	SSH (secure shell)
514	RSH (remote shell)
23	Telnet

Transmission Control Protocol

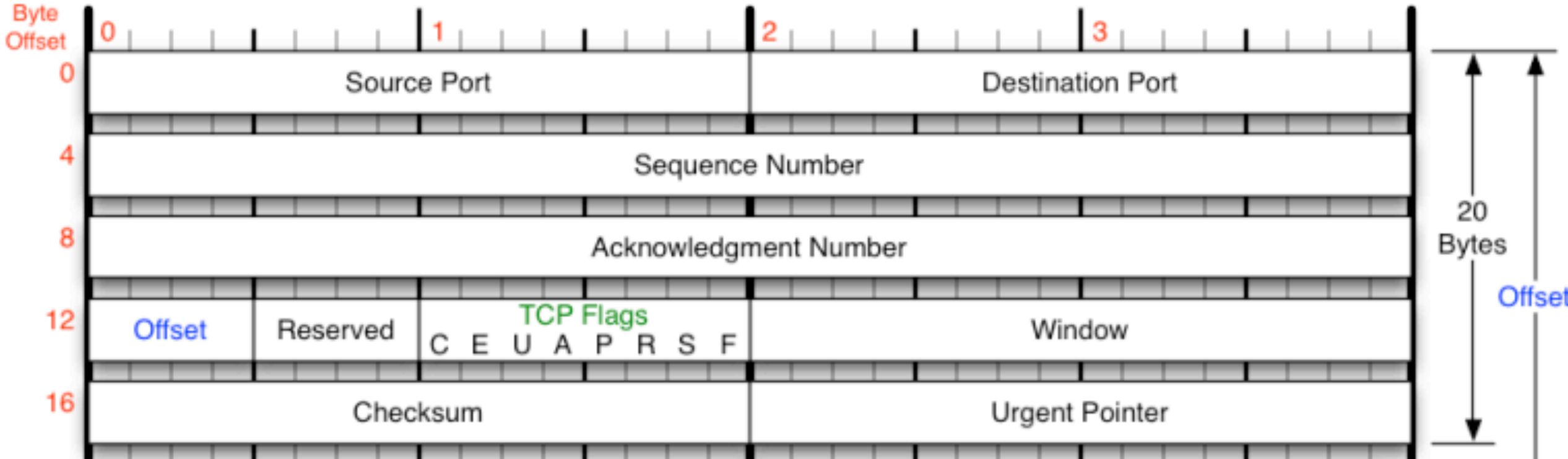
Bytes in application data stream numbered with a 32-bit *sequence number*

Data sent in *segments:* sequences of contiguous bytes sent in a single IP datagram

There are two logical data streams in a TCP session, one in each direction

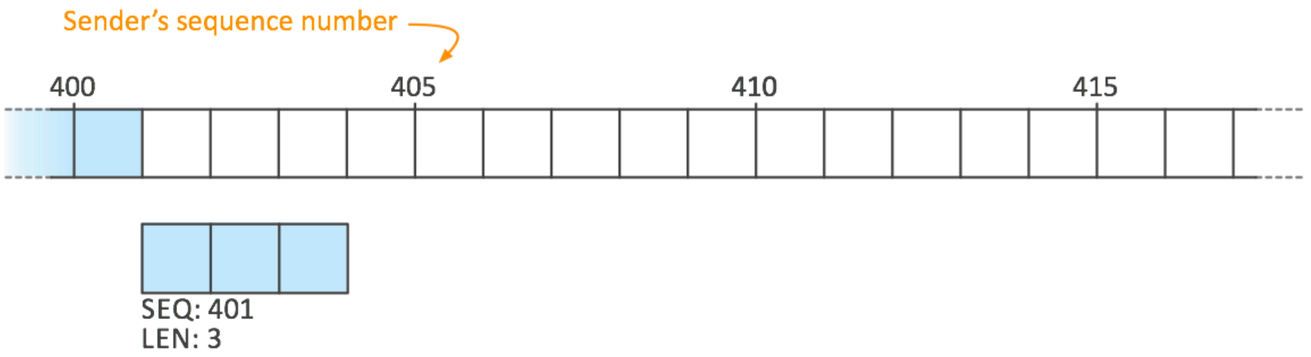
Transmission Control Protocol

Sequence number in packet header is seq. number of first byte of payload
Acknowledgement number is seq number of next expected byte of stream
in opposite direction



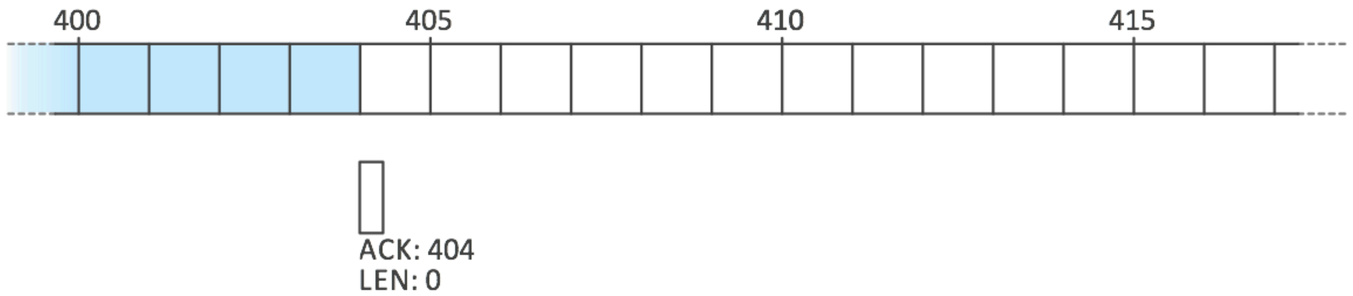
Transmission Control Protocol

- Sender sends 3 byte segment
- Sequence number indicates where data belongs in byte sequence (at byte 401)
  - *Note:* Wireshark shows *relative* sequence numbers



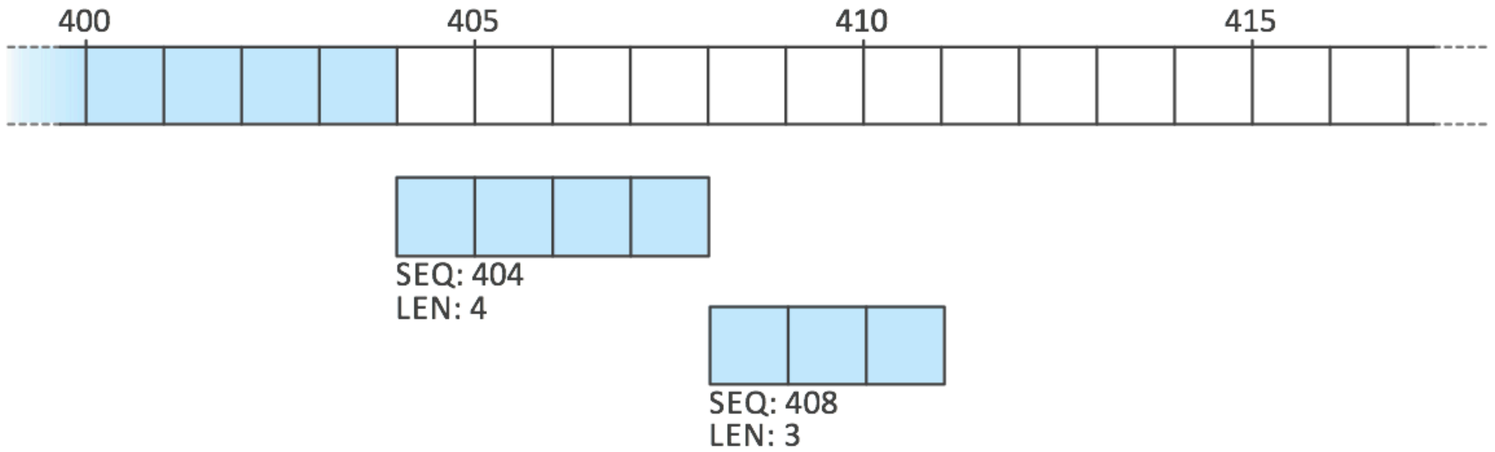
TCP ACKs

- Receiver acknowledges received data
  - Sets ACK flag in TCP header
  - Sets acknowledgement number to indicate next expected byte in sequence



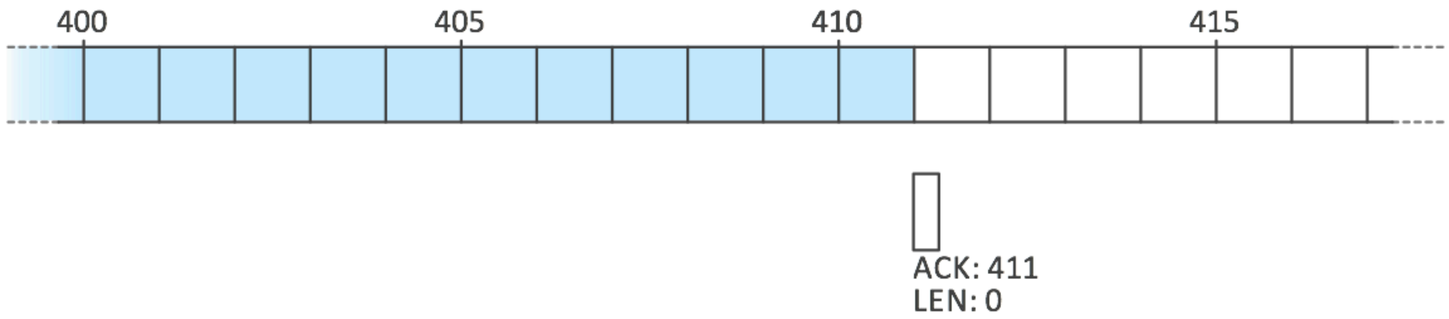
Transmission Control Protocol

- Sender may send several segments before receiving acknowledgement



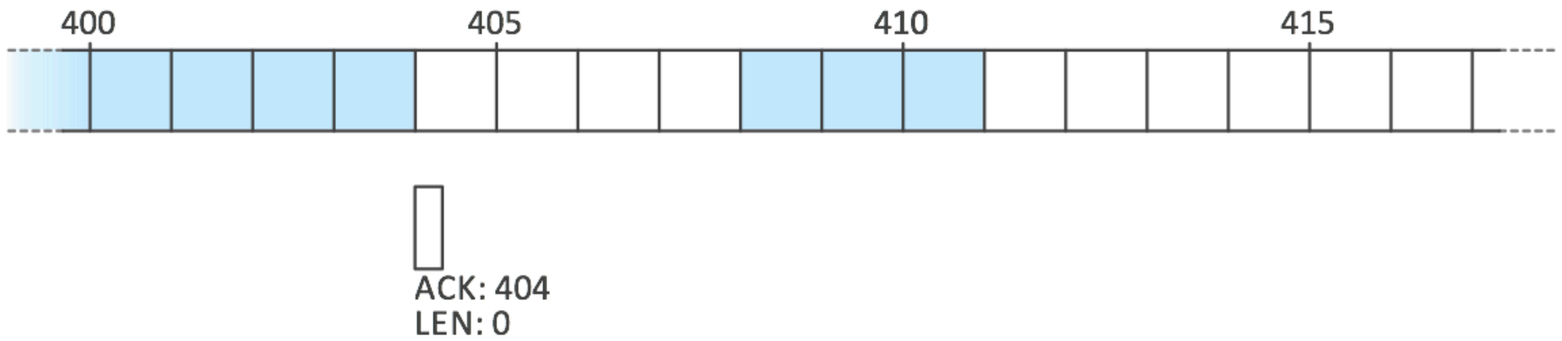
Transmission Control Protocol

- Sender may send several segments before receiving acknowledgement
- Receiver always acknowledges with seq. no. of next expected byte



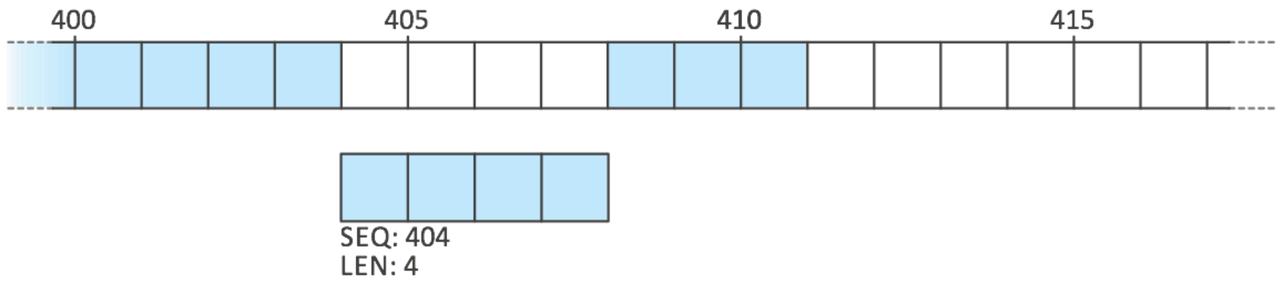
Transmission Control Protocol

- *What if the first packet is dropped in network?*
- Receiver always acknowledges with seq. no. of next expected byte



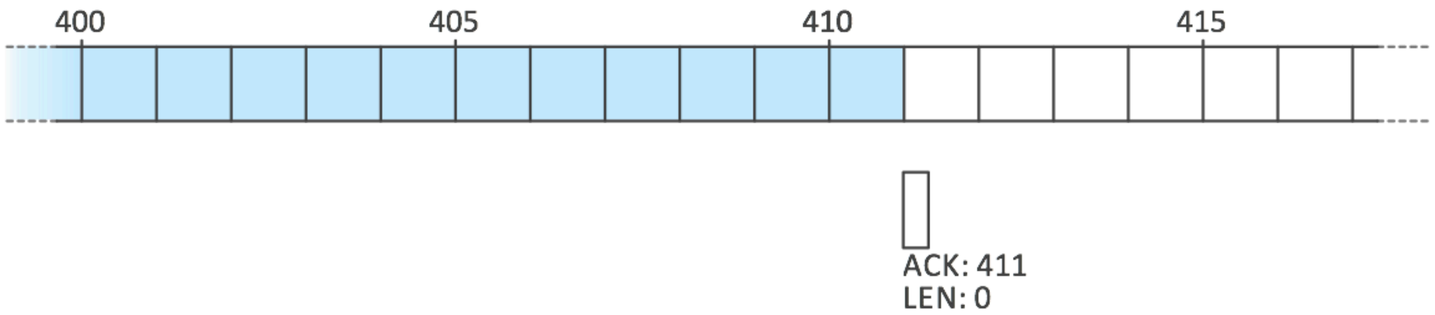
Transmission Control Protocol

- *What if the first packet is dropped in network?*
- Receiver always acknowledges with seq. no. of next expected byte
- Sender retransmits lost segment



Transmission Control Protocol

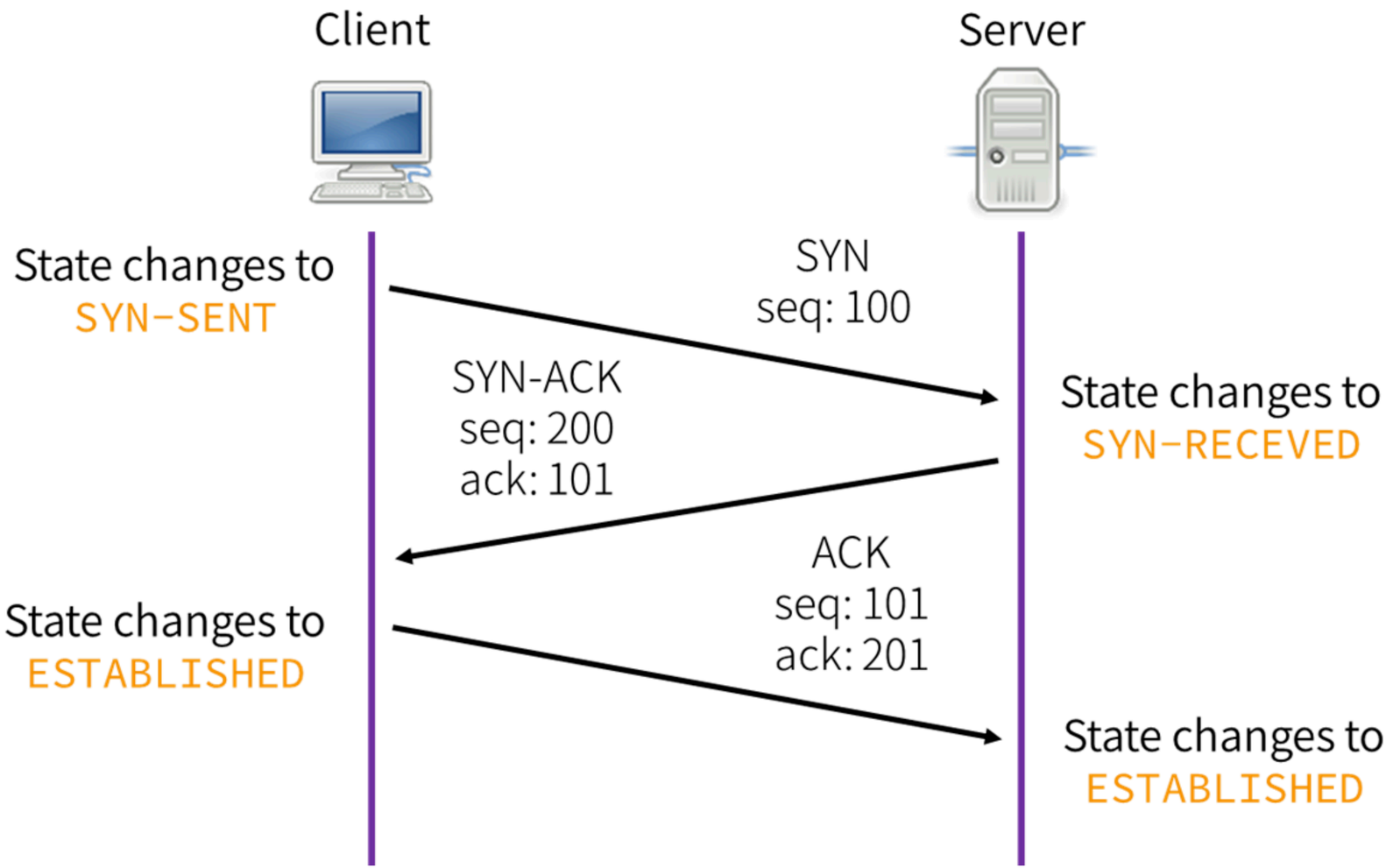
- *What if the first packet is dropped in network?*
- Sender retransmits lost segment
- Receiver always acknowledges with seq. no. of next expected byte



Transmission Control Protocol

- ACKs may be piggybacked on data flowing in opposite direction or sent without data
- All packets after initial connection setup will carry an acknowledgement
- Sequence numbers wrap around:
  …, 2^{32}-2, 2^{32}-1, 0, 1, 2, …

Starting a Connection

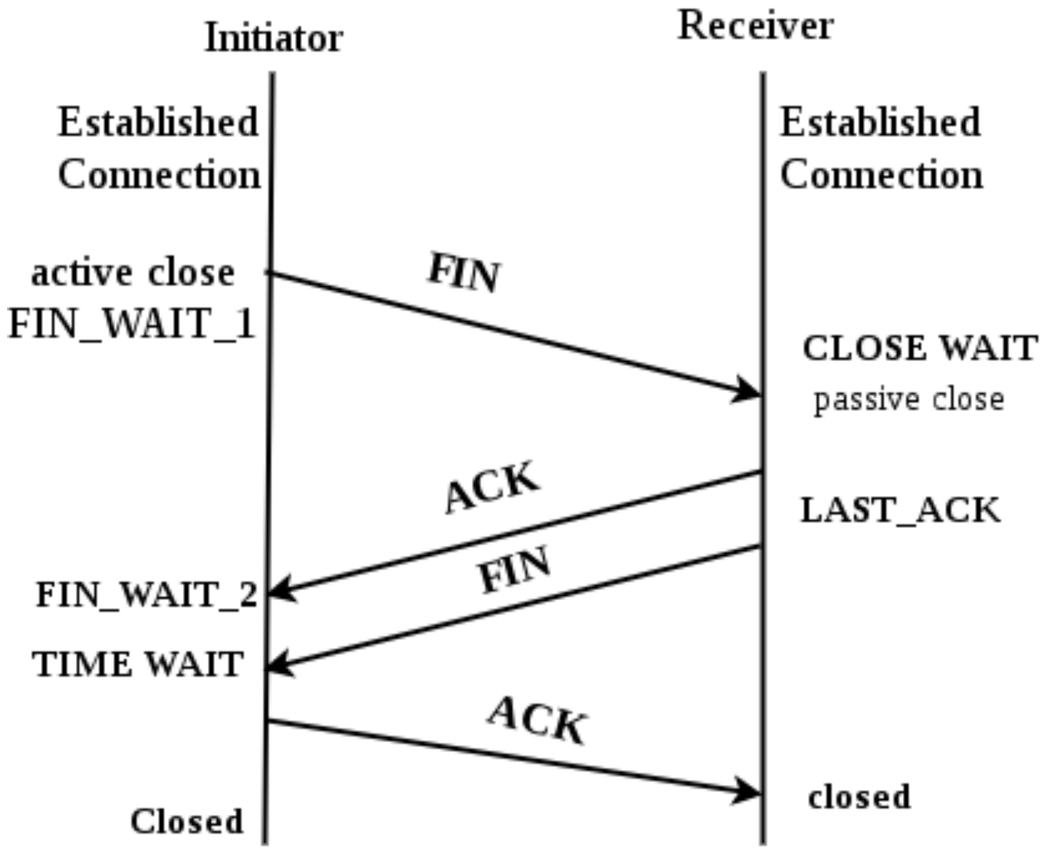


Ending a Connection

Sends packet with FIN flag set
Must have ACK flag with valid seqnum

Peer receiving FIN packet acknowledges receipt of FIN packet with ACK
FIN “consumes” one byte of seq. number

Eventually other side sends packet with FIN flag set:
This terminates the TCP session



TCP Connection Reset

TCP designed to handle possibility of spurious TCP packets (e.g. from previous connections)

Packets that are invalid given current state of session generate a reset
- If a connection exists, it is torn down
- Packet with RST flag sent in response

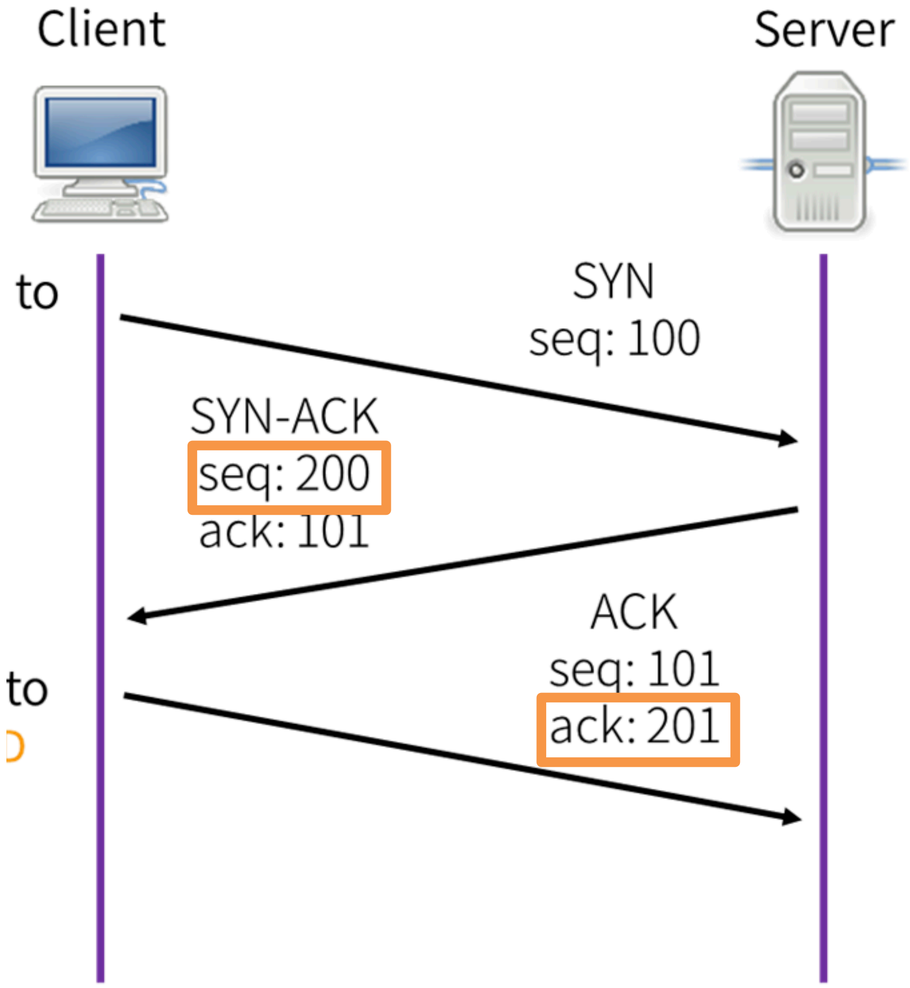
If a host receives a TCP packet with RST flag, it tears down the connection

TCP Connection Spoofing

Can we impersonate another host when *initiating* a connection?

Off-path attacker can send initial SYN to server …
… but cannot complete three-way handshake without seeing the server's sequence number

1 in 2^{32} chance to guess right if initial sequence number chosen uniformly at random



TCP Reset Attack

Can we reset an *existing* TCP connection?

Need to know port numbers (16 bits)
- Initiator's port number usually chosen random by OS
- Responder's port number may be well-known port of service

There is leeway in sequence numbers B will accept
- Must be within window size (32-64K on most modern OSes)

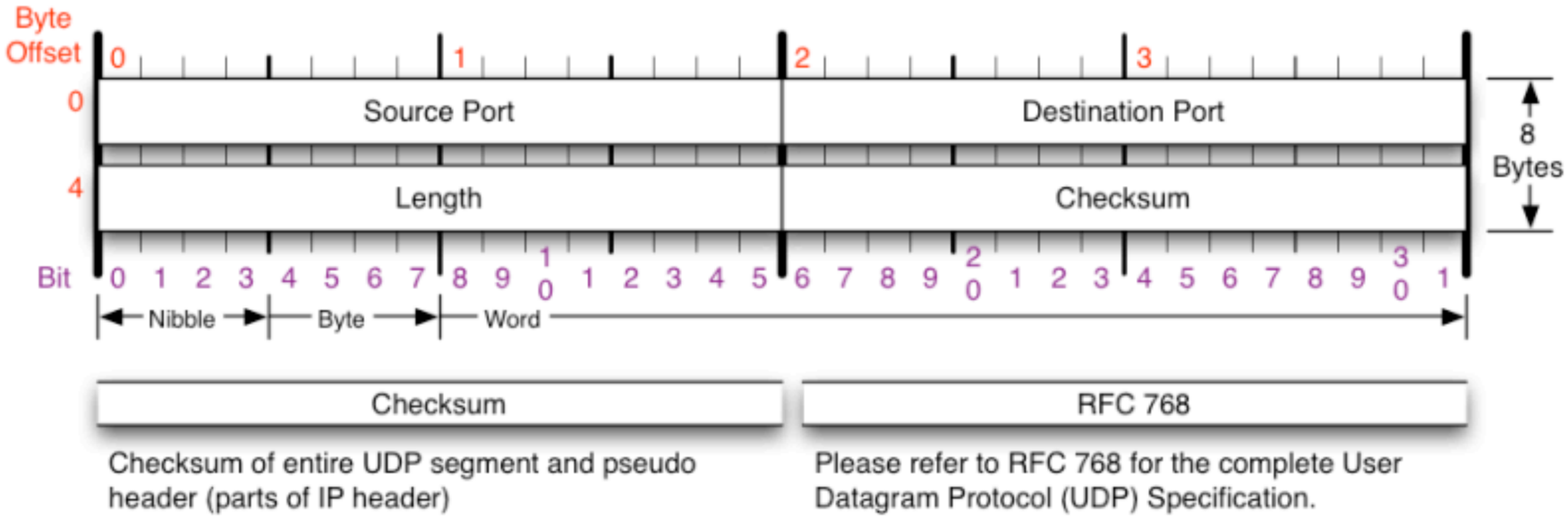
1 in $2^{16+32}/W$ (where W is window size) chance to guess right

UDP (User Datagram Protocol)

Sometimes we *do* only want best-effort delivery

User Datagram Protocol (UDP) is a transport layer protocol that is essentially a wrapper around IP

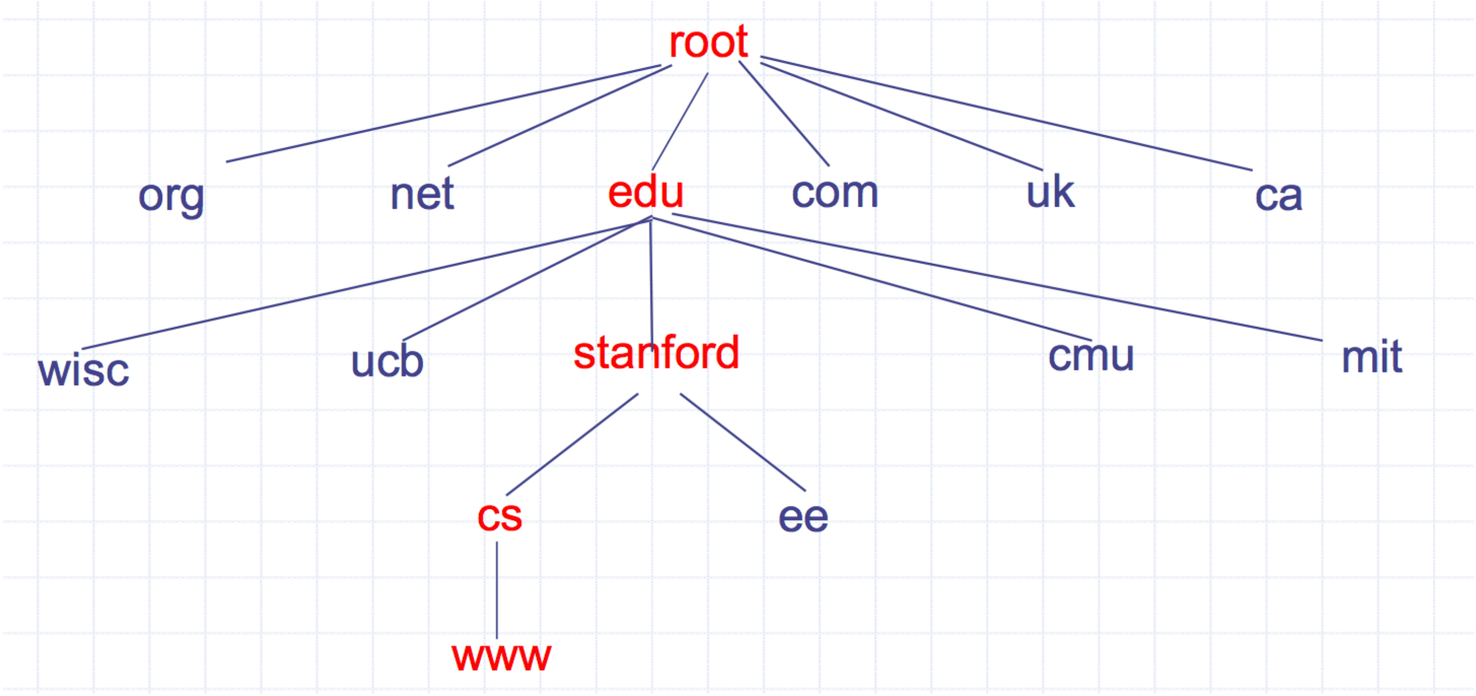
Adds ports to demultiplex traffic by applications



DNS

Application-layer protocols (and people) usually refer to Internet host by host name (e.g., google.com)

DNS is a delegatable, hierarchical name space



DNS Record

A DNS server has a set of records it authoritatively knows about

```
$ dig bob.ucsd.edu

;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 30439
;; flags: qr aa rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 3, ADDITIONAL: 6

;; QUESTION SECTION:
;bob.ucsd.edu.      IN A

;; ANSWER SECTION:
bob.ucsd.edu.    3600 IN A  132.239.80.176

;; AUTHORITY SECTION:
ucsd.edu.    3600 IN NS ns0.ucsd.edu.
ucsd.edu.    3600 IN NS ns1.ucsd.edu.
ucsd.edu.    3600 IN NS ns2.ucsd.edu.
```

DNS Root Name Servers

In total, there are 13 main **DNS root servers**, each of which is named with the letters 'A' to 'M'.

HOSTNAME	IP ADDRESSES	MANAGER
a.root-servers.net	198.41.0.4, 2001:503:ba3e::2:30	VeriSign, Inc.
b.root-servers.net	199.9.14.201, 2001:500:200::b	University of Southern California (ISI)
c.root-servers.net	192.33.4.12, 2001:500:2::c	Cogent Communications
d.root-servers.net	199.7.91.13, 2001:500:2d::d	University of Maryland
e.root-servers.net	192.203.230.10, 2001:500:a8::e	NASA (Ames Research Center)
f.root-servers.net	192.5.5.241, 2001:500:2f::f	Internet Systems Consortium, Inc.
g.root-servers.net	192.112.36.4, 2001:500:12::d0d	US Department of Defense (NIC)
h.root-servers.net	198.97.190.53, 2001:500:1::53	US Army (Research Lab)
i.root-servers.net	192.36.148.17, 2001:7fe::53	Netnod
j.root-servers.net	192.58.128.30, 2001:503:c27::2:30	VeriSign, Inc.
k.root-servers.net	193.0.14.129, 2001:7fd::1	RIPE NCC
l.root-servers.net	199.7.83.42, 2001:500:9f::42	ICANN
m.root-servers.net	202.12.27.33, 2001:dc3::35	WIDE Project

Caching

DNS responses are cached

- Quick response for repeated translations
- NS records for domains also cached

DNS negative queries are cached

- Save time for nonexistent sites, e.g. misspelling

Cached data periodically times out

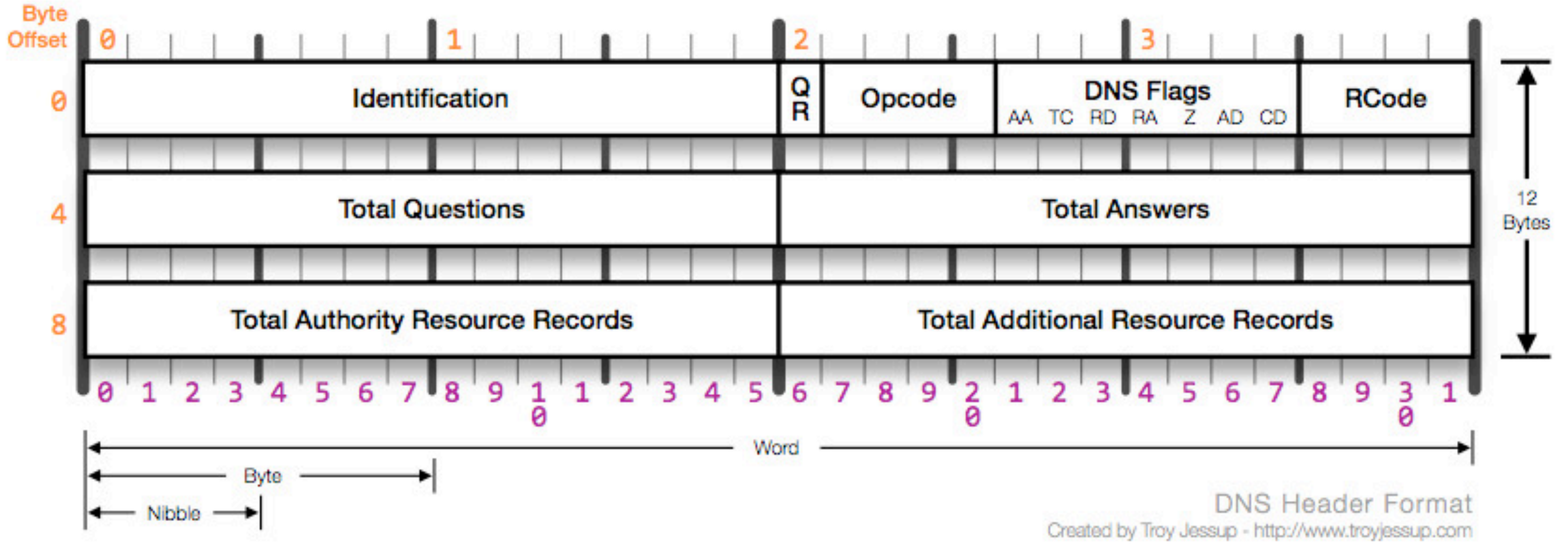
- Lifetime (TTL) of data controlled by owner of data
- TTL passed with every record

DNS Packet

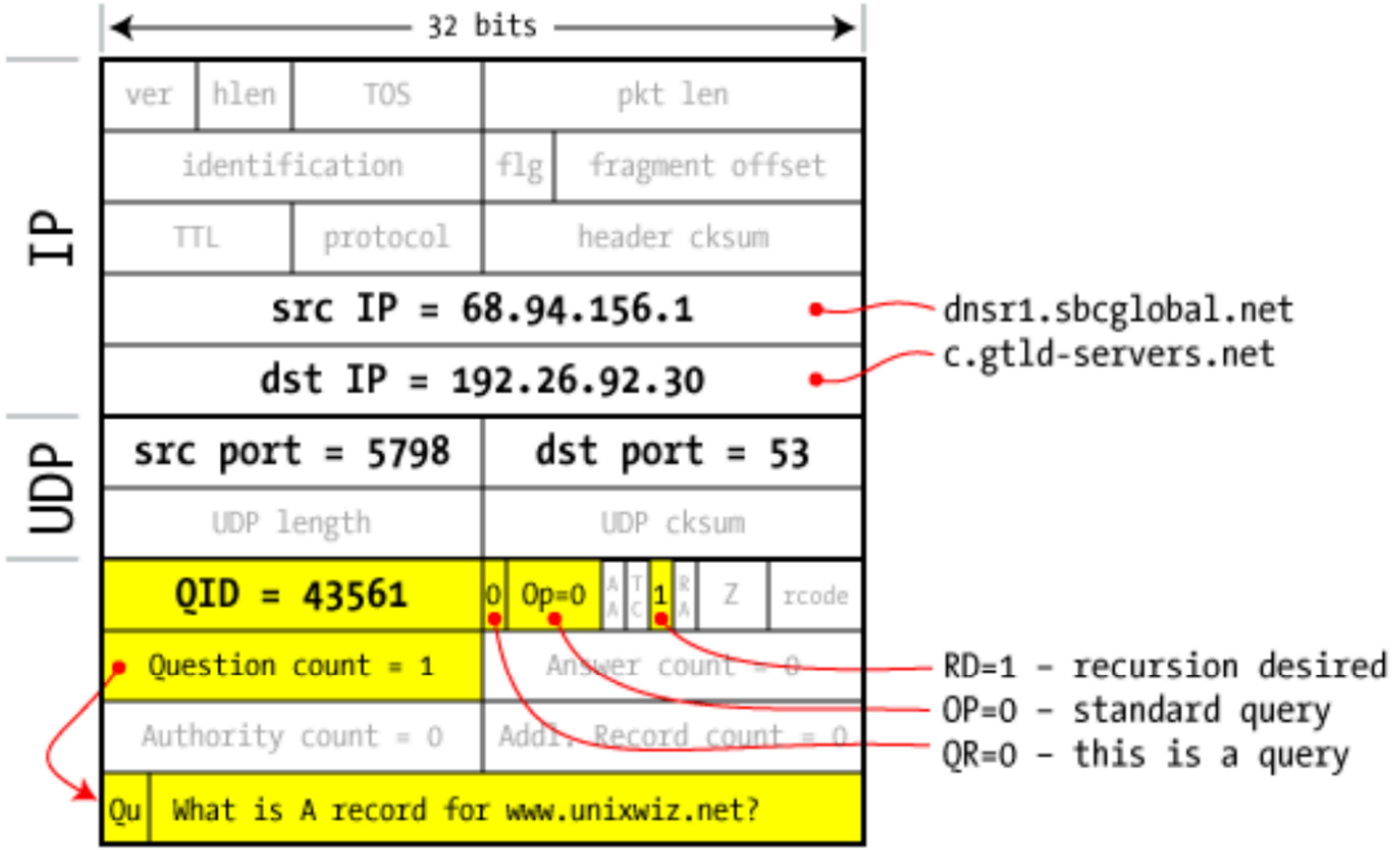
DNS requests sent over UDP

Four sections: questions, answers, authority, additional records

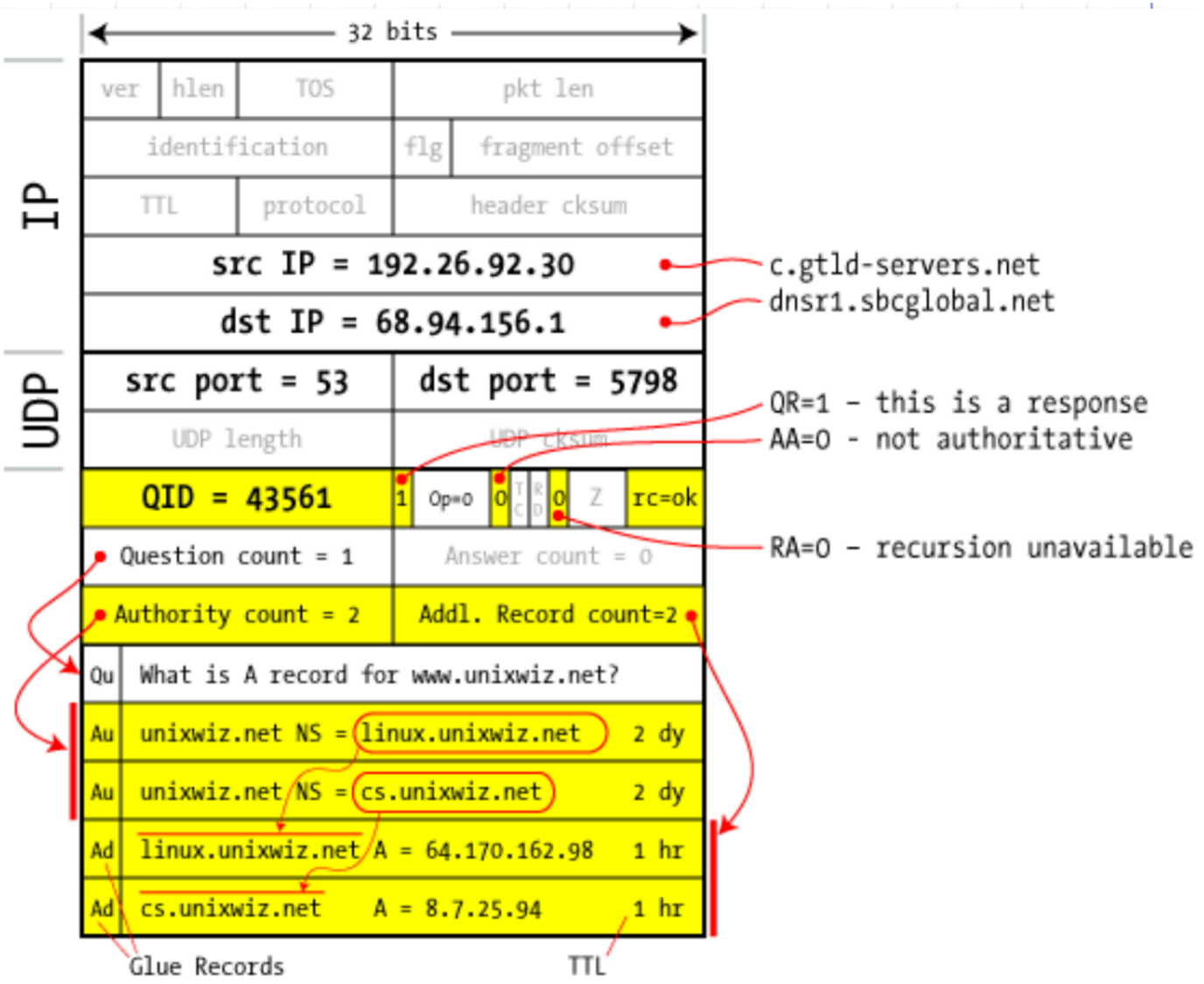
Query ID:
16 bit random value
Links response to query



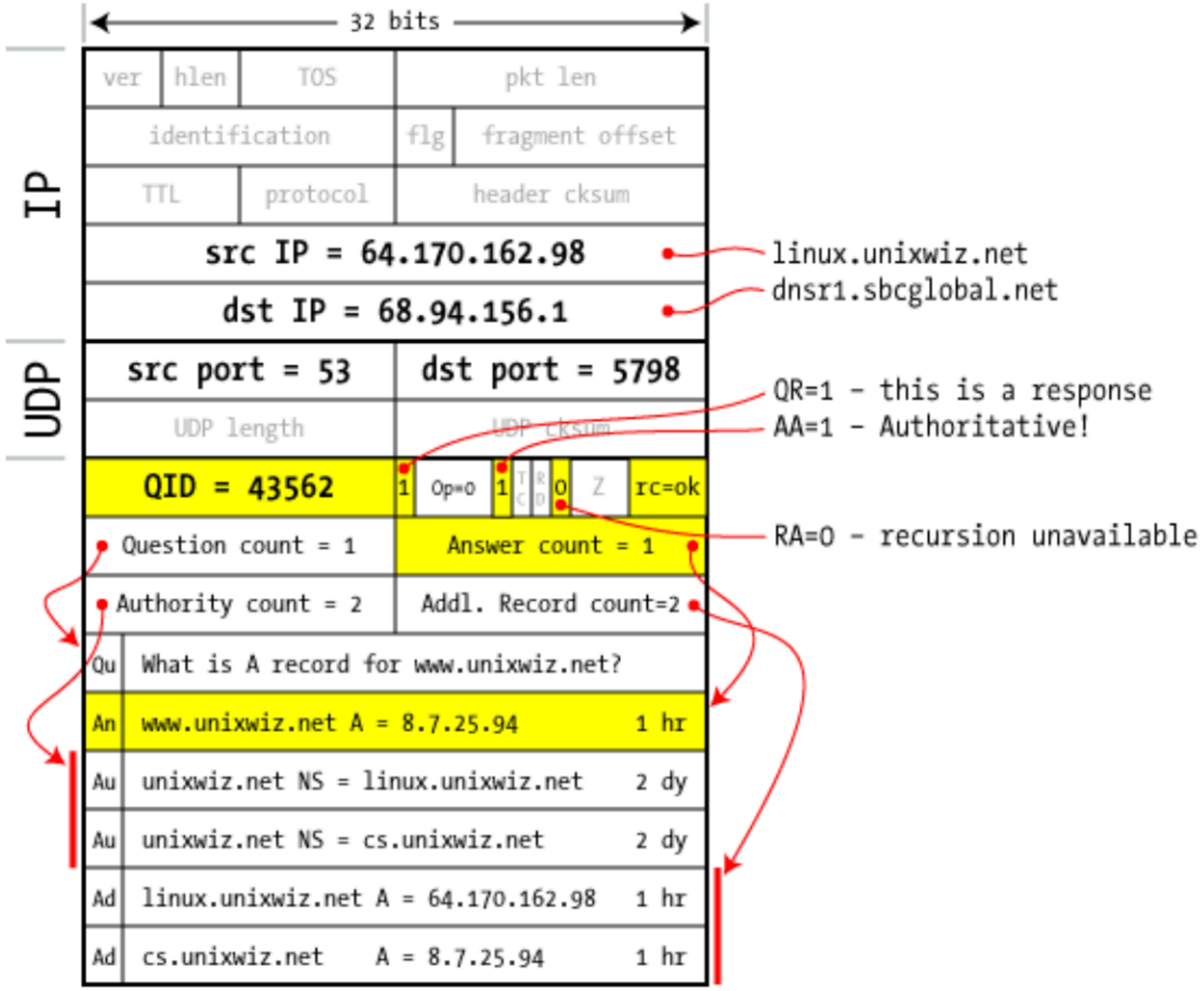
Request


32 bits
IP
UDP
ver
hlen
TOS
pkt len
identification
flg
fragment offset
TTL
protocol
header cksum
src IP = 68.94.156.1
dst IP = 192.26.92.30
src port = 5798
dst port = 53
UDP length
UDP cksum
QID = 43561
0
Op=0
1
Z
rcode
Question count = 1
Answer count = 0
Authority count = 0
Addl. Record count = 0
Qu
What is A record for www.unixwiz.net?
dnsr1.sbcglobal.net
c.gtld-servers.net
RD=1 - recursion desired
OP=0 - standard query
QR=0 - this is a query

Response


32 bits
IP
UDP
ver
hlen
TOS
pkt len
identification
flg
fragment offset
TTL
protocol
header cksum
src IP = 192.26.92.30
dst IP = 68.94.156.1
src port = 53
dst port = 5798
UDP length
UDP cksum
QID = 43561
1
Op=0
0
T C
R D
0
Z
rc=ok
Question count = 1
Answer count = 0
Authority count = 2
Addl. Record count=2
Qu
What is A record for www.unixwiz.net?
Au
unixwiz.net NS = linux.unixwiz.net
2 dy
Au
unixwiz.net NS = cs.unixwiz.net
2 dy
Ad
linux.unixwiz.net A = 64.170.162.98
1 hr
Ad
cs.unixwiz.net A = 8.7.25.94
1 hr
Glue Records
TTL
c.gtld-servers.net
dnsr1.sbcglobal.net
QR=1 - this is a response
AA=0 - not authoritative
RA=0 - recursion unavailable

Authoritative Response



DNS Security

Users/hosts trust the host-address mapping provided by DNS

Used as basis for many security policies:

Browser same origin policy, URL address bar

Interception of requests or compromise of DNS servers can result in incorrect or malicious responses

DNSSEC Fixes, but nobody uses. Use TLS!!

DNS Spoofing

Scenario: DNS client issues query to server

Attacker would like to inject a fake reply
  Attacker does not see query or real response

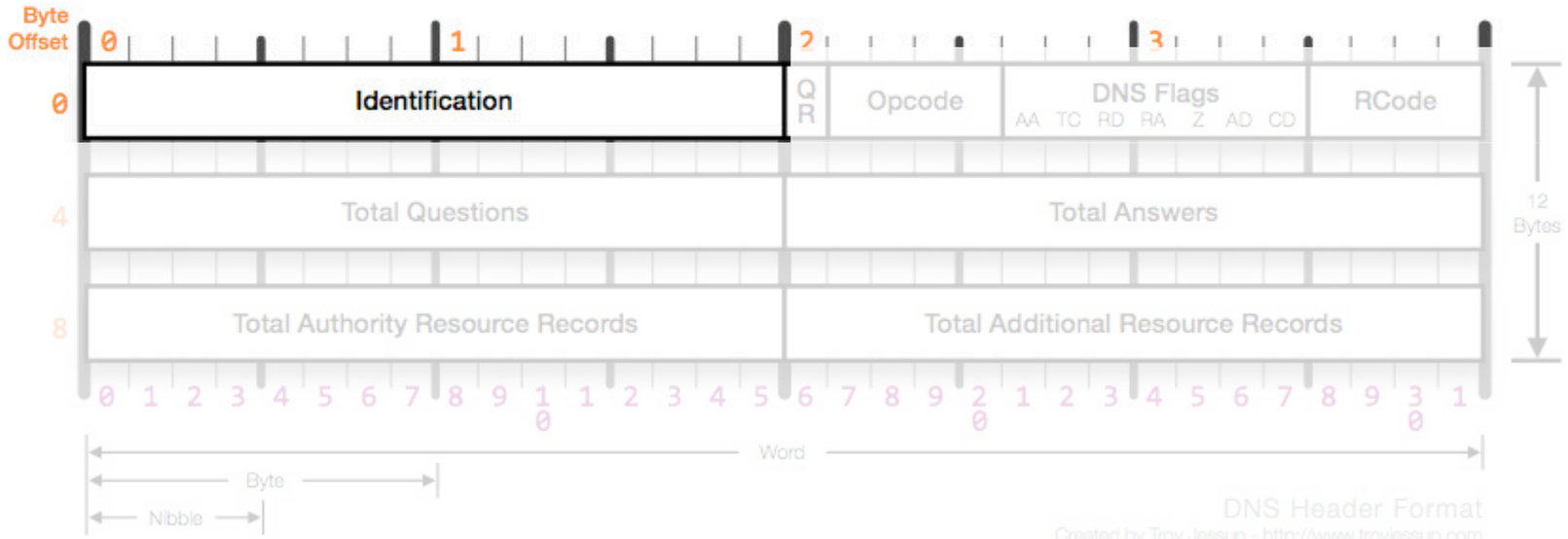
How does client authenticate response?

DNS Spoofing

How does client authenticate response?

UDP port numbers must match
Destination port usually port 53 by convention

16-bit query ID must match



DNS Cache Poisoning

Recursive resolvers cache records to avoid repeating recursive resolution process for each query

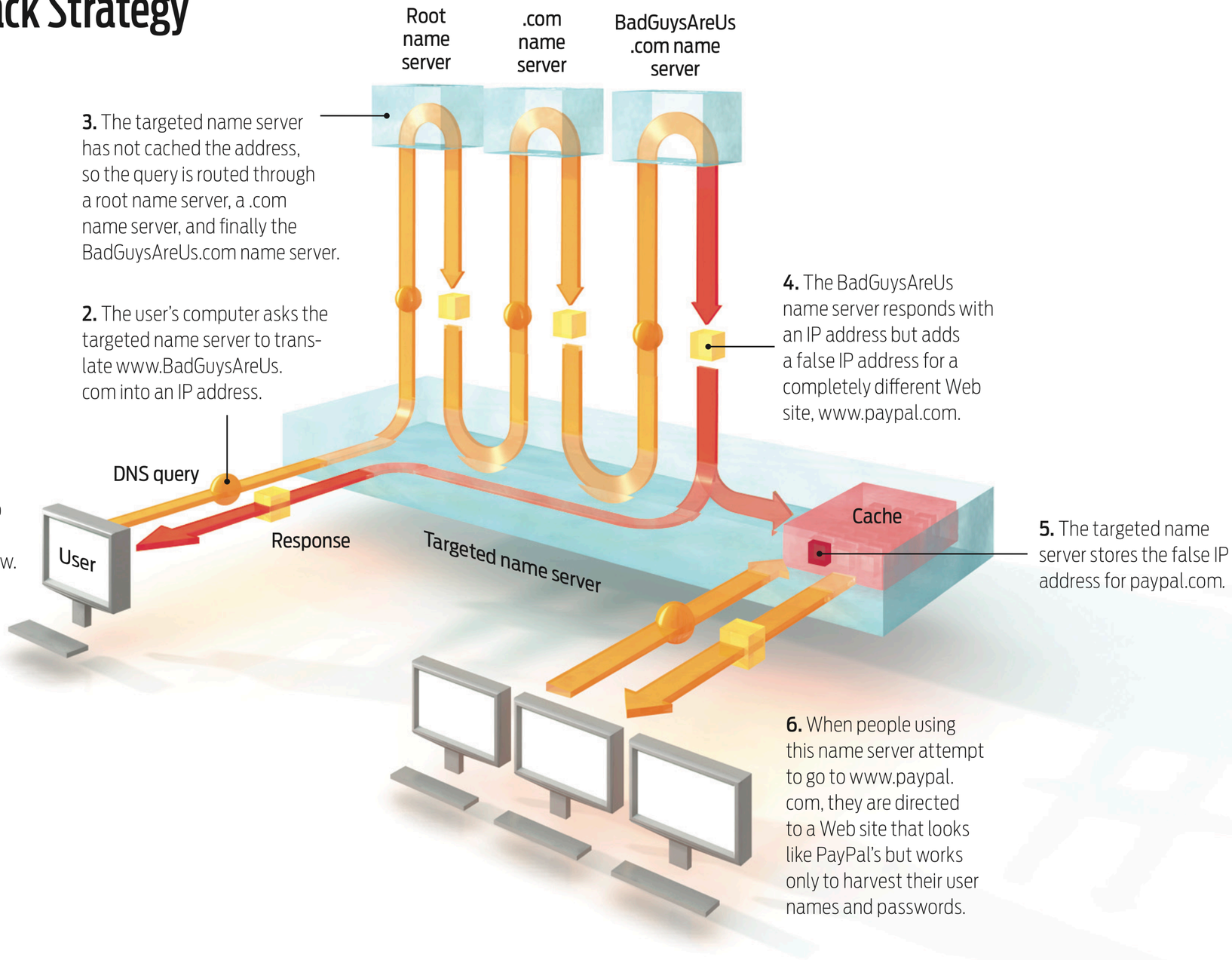
Lifetime of record determined by record TTL

Could also be evicted from cache due to limited memory

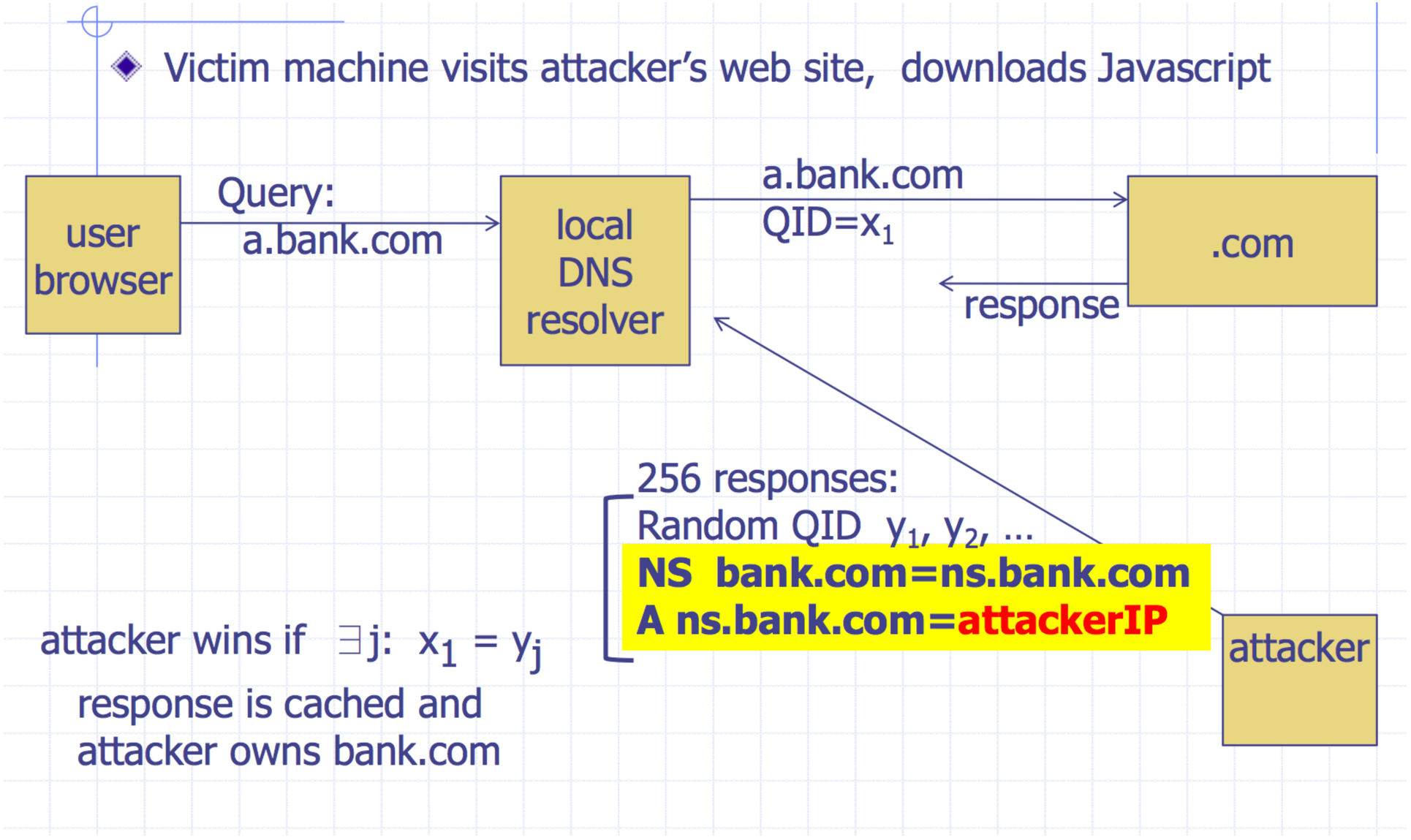
Injecting spoofed records into a resolver's cache is called *DNS cache poisoning*

No protocol-defined way for to refresh cached record

Early Attack Strategy

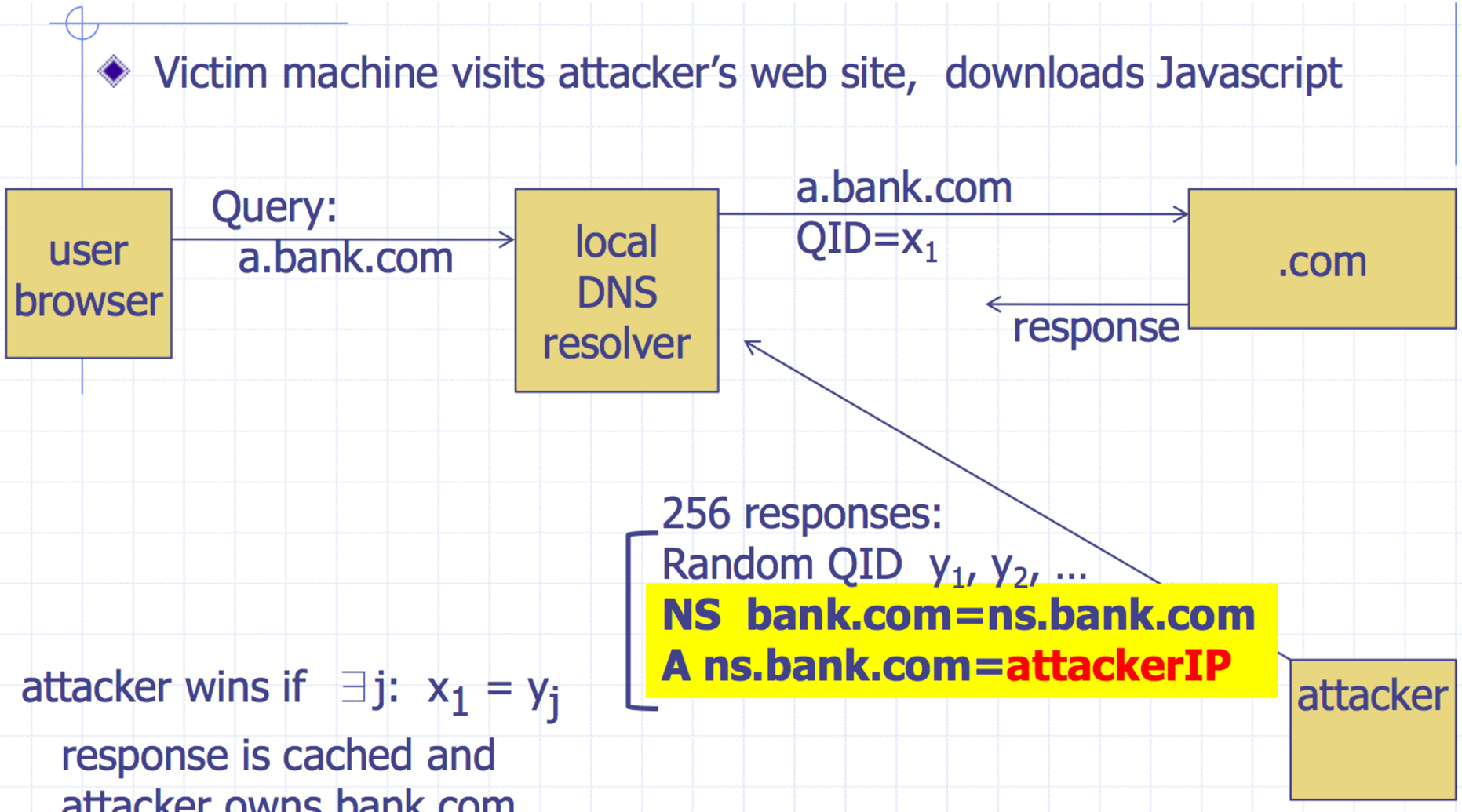


Kaminsky Attack



Try Again!

- Victim machine visits attacker's web site, downloads Javascript



Defenses

Increase QueryID. But how? Don’t want to change packet.

Randomize src port, additional 11 bits

- Now attack takes several hours

Conclusion

The network is out to get you.