EECS 388

Introduction to Computer Security

Lecture 12:

Networking 102

October 3, 2024
Prof. Chen

Web and Network Security

Last two weeks:

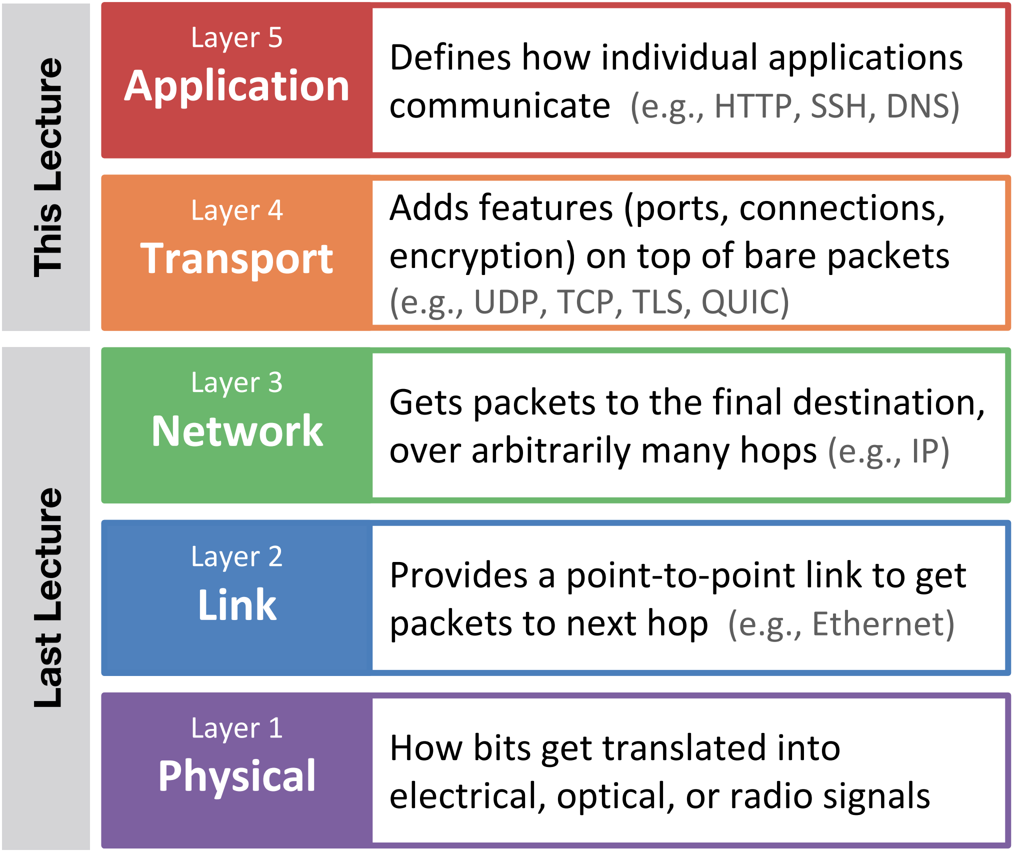
- The Web Platform
- Web Attacks and Defenses
- HTTPS and the Web PKI
- HTTPS Attacks and Defenses

This week:

- Networking 101
- **Networking 102**

Later:

- Network Defense
- Privacy and Anonymity
- Censorship and Circumvention



This Lecture

Layer 5
Application
Defines how individual applications communicate (e.g., HTTP, SSH, DNS)

Layer 4
Transport
Adds features (ports, connections, encryption) on top of bare packets (e.g., UDP, TCP, TLS, QUIC)

Last Lecture

Layer 3
Network
Gets packets to the final destination, over arbitrarily many hops (e.g., IP)

Layer 2
Link
Provides a point-to-point link to get packets to next hop (e.g., Ethernet)

Layer 1
Physical
How bits get translated into electrical, optical, or radio signals

Packet Capture and Analysis

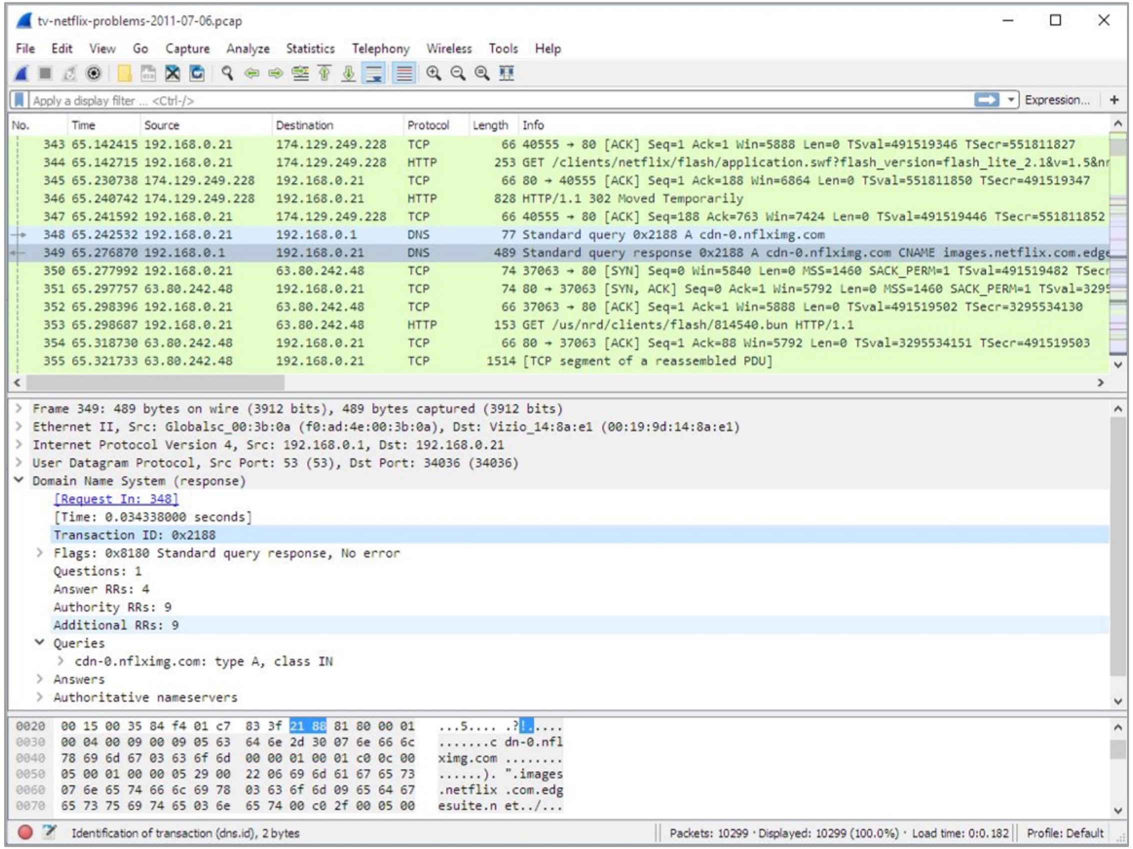
Hosts can record all packets arriving on their network interface (“packet sniffing”).

Standard data format: pcap

Wireshark software:

- Examine packets and decode each protocol layer.
- Filter packets by properties.
- Reassemble TCP packets to show complete data stream.
- Decrypt TLS, if provided the session key (normally requires control of client or server).

You’ll experiment with Wireshark in lab this week and in Project 3.



```
No.     Time      Source          Destination     Protocol Length Info
    343 65.142415 192.168.0.21    174.129.249.228 TCP        66 40555 → 80 [ACK] Seq=1 Ack=1 Win=5888 Len=0 TSval=491519346 TSecr=551811827
    344 65.142715 192.168.0.21    174.129.249.228 HTTP      253 GET /clients/netflix/flash/application.swf?flash_version=flash_lite_2.1&v=1.5&nr
    345 65.230738 174.129.249.228 192.168.0.21    TCP        66 80 → 40555 [ACK] Seq=1 Ack=188 Win=6864 Len=0 TSval=551811850 TSecr=491519347
    346 65.240742 174.129.249.228 192.168.0.21    HTTP      828 HTTP/1.1 302 Moved Temporarily
    347 65.241592 192.168.0.21    174.129.249.228 TCP        66 40555 → 80 [ACK] Seq=188 Ack=763 Win=7424 Len=0 TSval=491519446 TSecr=551811852
    348 65.242532 192.168.0.21    192.168.0.1     DNS        77 Standard query 0x2188 A cdn-0.nflximg.com
    349 65.276870 192.168.0.1     192.168.0.21    DNS       489 Standard query response 0x2188 A cdn-0.nflximg.com CNAME images.netflix.com.edge
    350 65.277992 192.168.0.21    63.80.242.48    TCP        74 37063 → 80 [SYN] Seq=0 Win=5840 Len=0 MSS=1460 SACK_PERM=1 TSval=491519482 TSecr
    351 65.297757 63.80.242.48    192.168.0.21    TCP        74 80 → 37063 [SYN, ACK] Seq=0 Ack=1 Win=5792 Len=0 MSS=1460 SACK_PERM=1 TSval=3295
    352 65.298396 192.168.0.21    63.80.242.48    TCP        66 37063 → 80 [ACK] Seq=1 Ack=1 Win=5888 Len=0 TSval=491519502 TSecr=3295534130
    353 65.298687 192.168.0.21    63.80.242.48    HTTP      153 GET /us/nrd/clients/flash/814540.bun HTTP/1.1
    354 65.318730 63.80.242.48    192.168.0.21    TCP        66 80 → 37063 [ACK] Seq=1 Ack=88 Win=5792 Len=0 TSval=3295534151 TSecr=491519503
    355 65.321733 63.80.242.48    192.168.0.21    TCP      1514 [TCP segment of a reassembled PDU]
```

```
> Frame 349: 489 bytes on wire (3912 bits), 489 bytes captured (3912 bits)
> Ethernet II, Src: Globalsc_00:3b:0a (f0:ad:4e:00:3b:0a), Dst: Vizio_14:8a:e1 (00:19:9d:14:8a:e1)
> Internet Protocol Version 4, Src: 192.168.0.1, Dst: 192.168.0.21
> User Datagram Protocol, Src Port: 53 (53), Dst Port: 34036 (34036)
v Domain Name System (response)
    [Request In: 348]
    [Time: 0.034338000 seconds]
    Transaction ID: 0x2188
  > Flags: 0x8180 Standard query response, No error
    Questions: 1
    Answer RRs: 4
    Authority RRs: 9
    Additional RRs: 9
  v Queries
      > cdn-0.nflximg.com: type A, class IN
  > Answers
  > Authoritative nameservers
```

```
0020  00 15 00 35 84 f4 01 c7  83 3f 21 88 81 80 00 01   ...5.... .?!.....
0030  00 04 00 09 00 09 05 63  64 6e 2d 30 07 6e 66 6c   .......c dn-0.nfl
0040  78 69 6d 67 03 63 6f 6d  00 00 01 00 01 c0 0c 00   ximg.com ........
0050  05 00 01 00 00 05 29 00  22 06 69 6d 61 67 65 73   ......). ".images
0060  07 6e 65 74 66 6c 69 78  03 63 6f 6d 09 65 64 67   .netflix .com.edg
0070  65 73 75 69 74 65 03 6e  65 74 00 c0 2f 00 05 00   esuite.n et../...
```

Identification of transaction (dns.id), 2 bytes

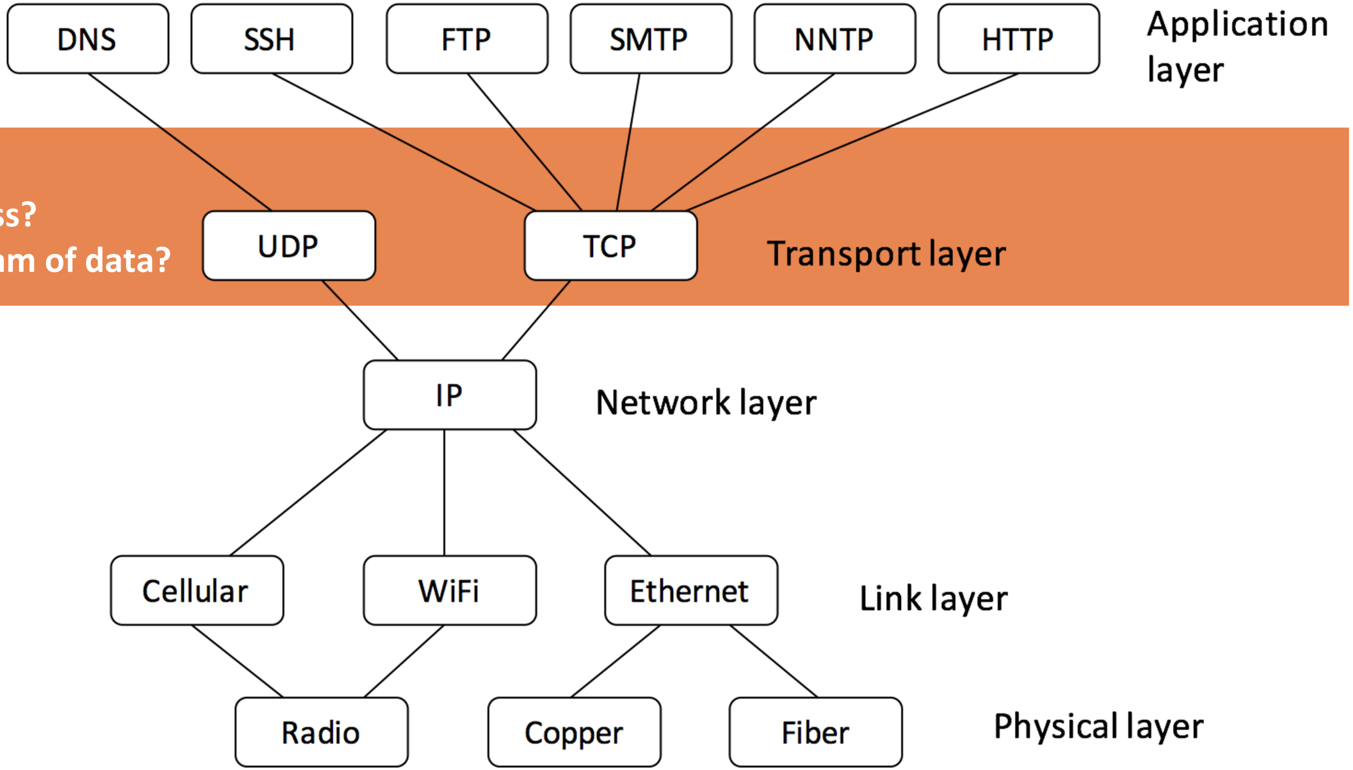
Packets: 10299 · Displayed: 10299 (100.0%) · Load time: 0:0.182

Profile: Default

Transport Layer

Transport | Adds features (ports, connections, encryption) on top of bare packets

How do I get to the right process?
How do I ensure a reliable stream of data?



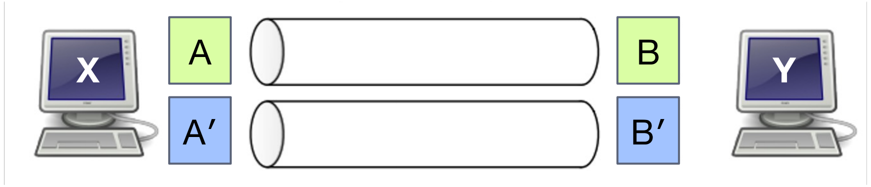
Ports

Transport Adds features (ports, connections, encryption) on top of bare packets

Issue: How do we send data to a *particular application process* running on a host?

Each application is identified by a 16-bit **port number** (1–65535).

TCP and UDP send data from port A on host X to port B on host Y.



With TCP, concurrent connections must have unique 4-tuples (X,A,Y,B).

Using different src. or dest. port allows multiple connections between same hosts.

Many destination port numbers are used for specific applications **by convention** (but servers can choose any port). Examples:

Port	Application
80	HTTP (web)
443	HTTPS (web via TLS)
25	SMTP (mail)
67	DHCP (host configuration)
22	SSH (secure shell)
23	Telnet (plaintext shell)

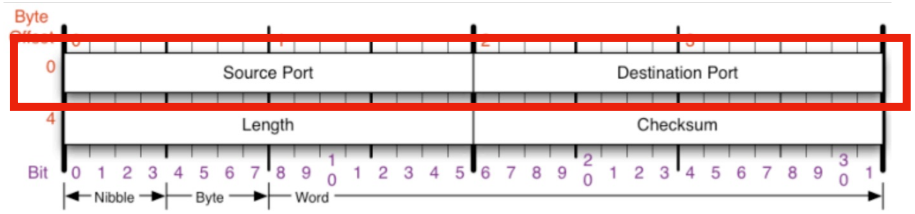
Ports <1024 are “privileged” – requires root

For client source ports, OS usually picks for you, uses high-numbered **ephemeral ports**, frequently in the range 32768-65535.

UDP

Transport Adds features (ports, connections, encryption) on top of bare packets

User Datagram Protocol (UDP) is a transport-layer protocol that is essentially just a wrapper around IP that adds ports to demultiplex traffic by application.



Applications that use UDP:

- DNS
- QUIC
- Many multiplayer games and real-time communications apps

UDP properties:

- Connectionless.
- Unreliable data transfer.
- No sequencing or flow control.
- No congestion control.
- **No security.**

UDP is highly vulnerable to **impersonation**: If **off-path** attacker knows what ports a client and server are using, it can inject packets (with spoofed source IP addresses) that appear to be part of the communication.

Using UDP allows/forces applications to provide missing properties at a higher level as needed, which sometimes allows better performance.

TCP

Transport Adds features (ports, connections, encryption) on top of bare packets

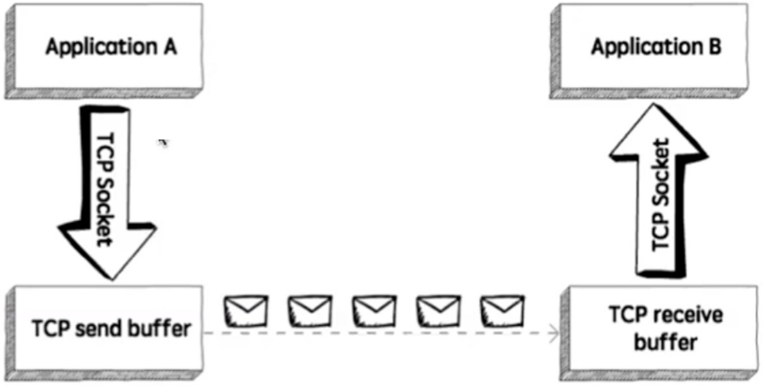
Transmission Control Protocol (TCP)

is a transport-layer protocol providing:

- **Connection-oriented semantics**
- **A reliable, bi-directional *byte stream***
- **Congestion control**

TCP does not provide: strong security.

Data carried in **segments**, each one IP packet.

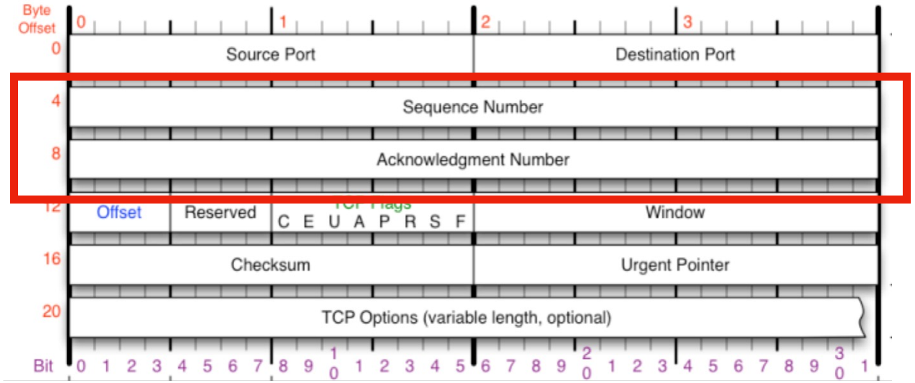


TCP provides these despite IP packets being dropped, re-ordered, and duplicated.

Each segment has 32-bit **sequence number** (where data sent fits in the stream) and **acknowledgement number** (what data is expected next).

Receiver **reassembles** segments as output stream. Sender **retransmits** unacknowledged segments.

TCP header:



TCP Handshake

Transport Adds features (ports, connections, encryption) on top of bare packets

TCP introduces the notion of a **session**.

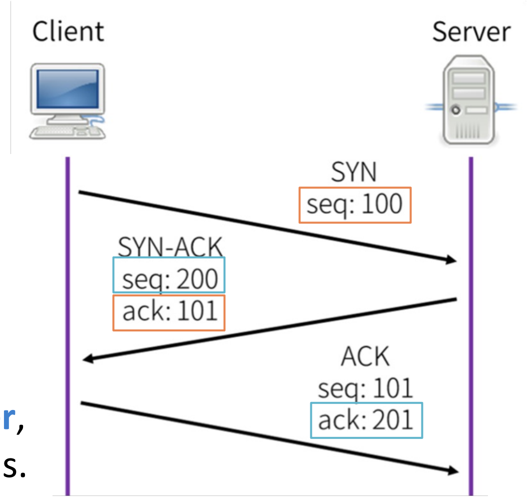
Server **listens on a port** to allow connections.
Clients **connect to the port** at the server's IP.

Every TCP session begins with a **three-way handshake**.

Special packets with **flag bits** set:

1. SYN
2. SYN+ACK
3. ACK

Client and server each pick random 32-bit **initial sequence number**, acknowledge the other's.



***On-path* attacks against TCP are trivial.**

Can **off-path** attackers ***impersonate*** another host when initiating a TCP connection?

Off-path attacker can spoof src. IP address and send initial SYN packet to server… but **can't complete three-way handshake** without guessing server's sequence number. (In theory, only 1 in 2^{32} chance.)

Can **off-path** attackers ***disrupt*** a TCP session?

In a **TCP reset attack**, attacker spoofs a packet with RST flag set. Needs right port numbers (~16 bits). Receive will close the connection if sequence number is within window size W of correct. W = 32-64K on modern OSes. (In theory, only 1 in $2^{16+32}/W$ chance.)

In practice, less-than-random values and clever **side-channels** often make off-path attacks easier.

Socket Programming

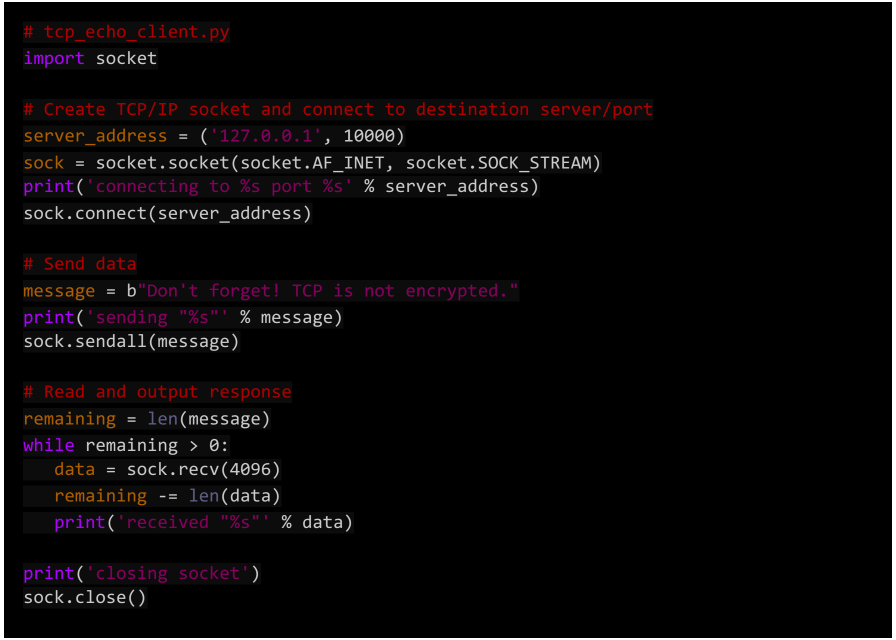
Transport | Adds features (ports, connections, encryption) on top of bare packets

TCP/IP is typically implemented by the OS.

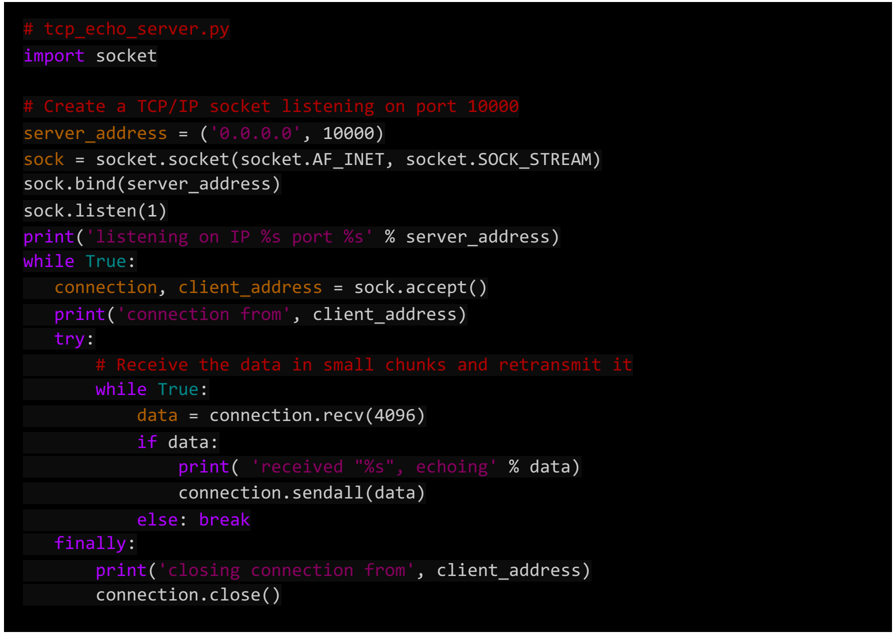
The socket API is a widely supported interface that let apps utilize TCP, UDP, other transports.

You’ll experiment with sockets in Project 3.

Examples below use the socket API from Python to implement “echo” client and server over TCP.



```python
# tcp_echo_client.py
import socket

# Create TCP/IP socket and connect to destination server/port
server_address = ('127.0.0.1', 10000)
sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
print('connecting to %s port %s' % server_address)
sock.connect(server_address)

# Send data
message = b"Don't forget! TCP is not encrypted."
print('sending "%s"' % message)
sock.sendall(message)

# Read and output response
remaining = len(message)
while remaining > 0:
    data = sock.recv(4096)
    remaining -= len(data)
    print('received "%s"' % data)

print('closing socket')
sock.close()
```

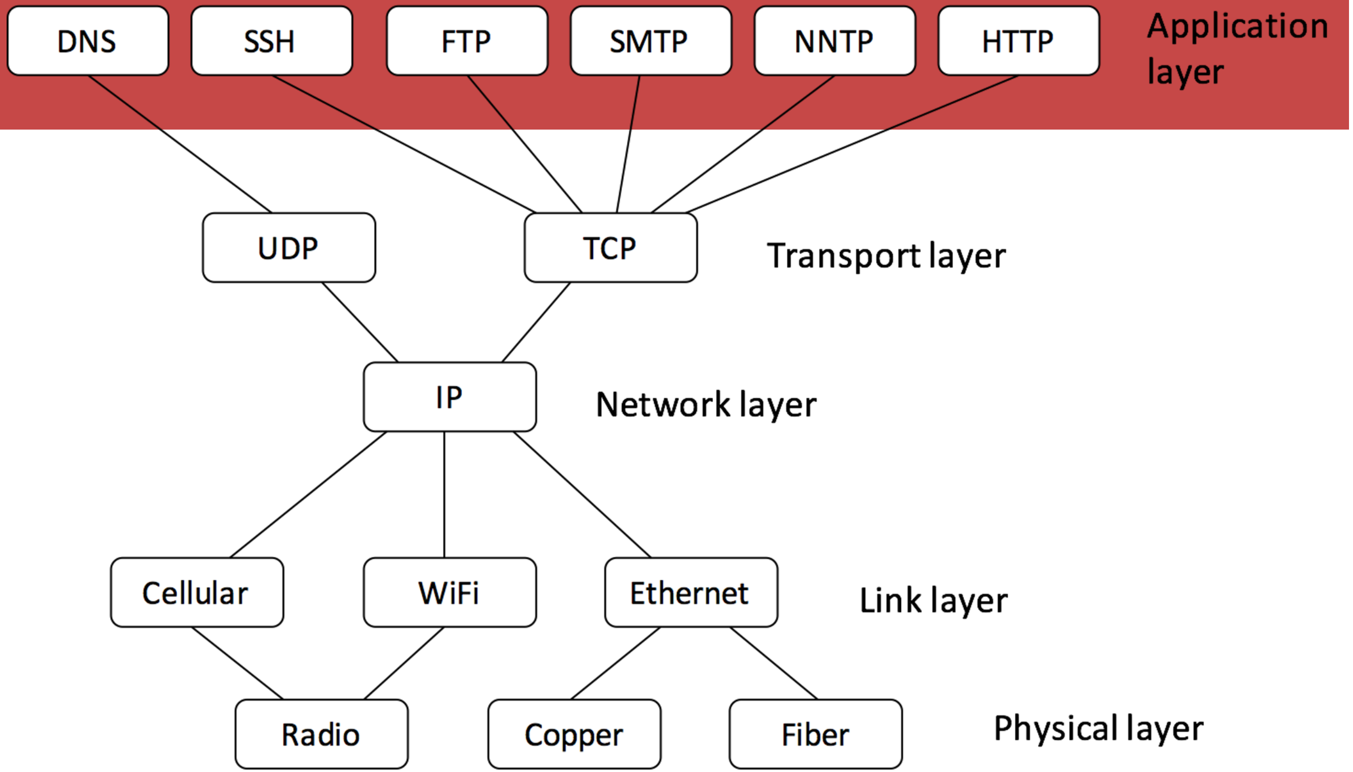


```python
# tcp_echo_server.py
import socket

# Create a TCP/IP socket listening on port 10000
server_address = ('0.0.0.0', 10000)
sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
sock.bind(server_address)
sock.listen(1)
print('listening on IP %s port %s' % server_address)
while True:
    connection, client_address = sock.accept()
    print('connection from', client_address)
    try:
        # Receive the data in small chunks and retransmit it
        while True:
            data = connection.recv(4096)
            if data:
                print( 'received "%s", echoing' % data)
                connection.sendall(data)
            else: break
    finally:
        print('closing connection from', client_address)
        connection.close()
```

Application Layer

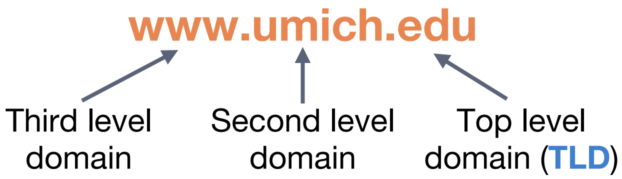
Application | Defines how individual applications communicate

How does the application structure data?

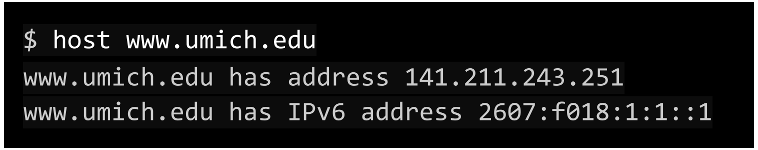


DNS

The **Domain Name System (DNS)** is a delegatable, hierarchical database.



DNS is used, e.g., to translate ("resolve") **hostnames** to IP addresses:



```
$ host www.umich.edu
www.umich.edu has address 141.211.243.251
www.umich.edu has IPv6 address 2607:f018:1:1::1
```

Decentralized design achieves global scale and avoids any single point of failure.

DNS operates at the application layer. OSes provide DNS client ("**name resolution**") service.

DNS associates names with **resource records**. Many **record types**, e.g.:

A	IPv4 address
AAAA	IPv6 address
MX	Inbound mail server
CAA	Certificate authority authorization
CNAME	Alias to another name
TXT	Arbitrary text
NS	Delegated name server

Two kinds of **DNS servers**:

Recursive servers: Answer queries from clients by asking other servers. ISPs/orgs. run them; also public servers: CloudFlare (**1.1.1.1**), Google (**8.8.8.8**)

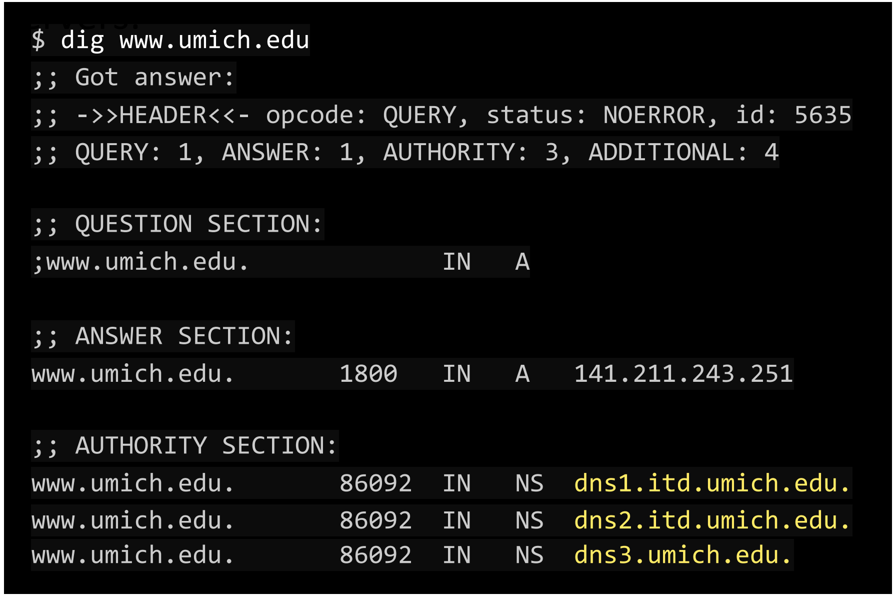
Authoritative servers: Domain owner run them to gives definitive answers for its part of namespace.

DNS Zones

Application Defines how individual applications communicate

Control over each region of namespace ("**zone**") delegated to **authoritative** servers.

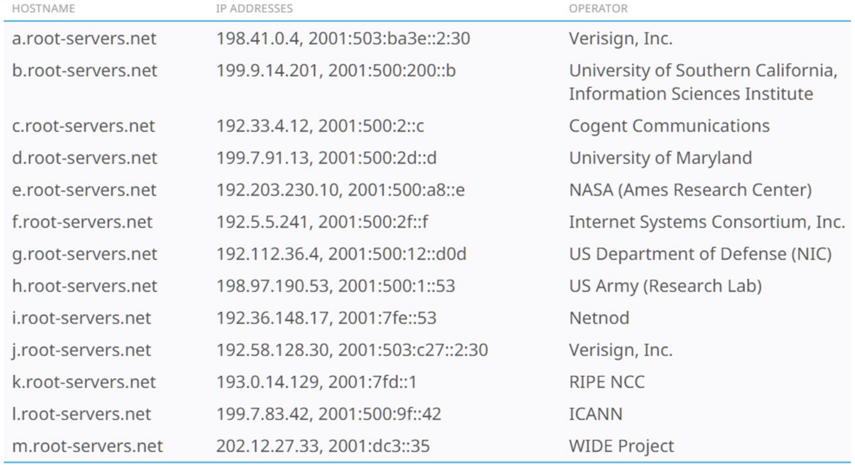
E.g., the zone "**umich.edu**" (which contains "www.umich.edu") has three authoritative



```
$ dig www.umich.edu
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 5635
;; QUERY: 1, ANSWER: 1, AUTHORITY: 3, ADDITIONAL: 4

;; QUESTION SECTION:
;www.umich.edu.              IN    A

;; ANSWER SECTION:
www.umich.edu.        1800   IN    A    141.211.243.251

;; AUTHORITY SECTION:
www.umich.edu.        86092  IN    NS   dns1.itd.umich.edu.
www.umich.edu.        86092  IN    NS   dns2.itd.umich.edu.
www.umich.edu.        86092  IN    NS   dns3.umich.edu.
```

The **root zone** ("**.**") contains all TLDs. Controlled by 13 authoritative servers.

DNS servers are provisioned with these IPs:

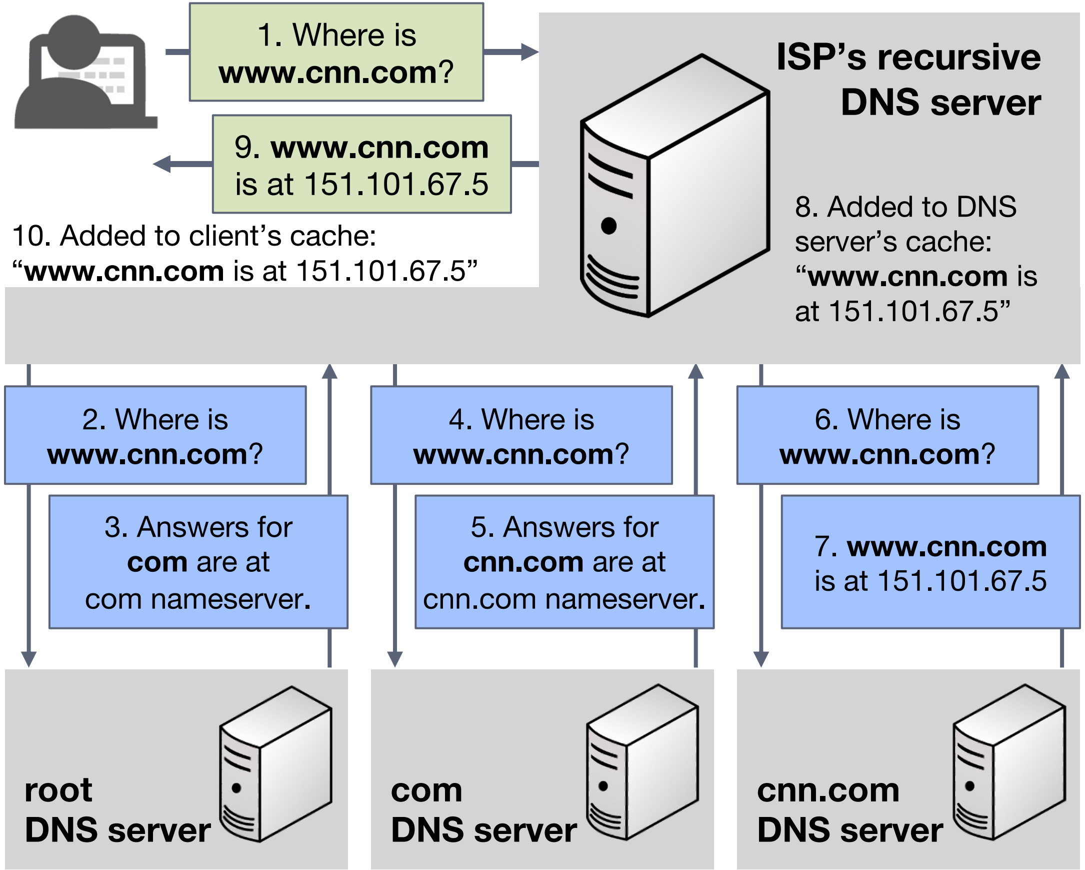


HOSTNAME	IP ADDRESSES	OPERATOR
a.root-servers.net	198.41.0.4, 2001:503:ba3e::2:30	Verisign, Inc.
b.root-servers.net	199.9.14.201, 2001:500:200::b	University of Southern California, Information Sciences Institute
c.root-servers.net	192.33.4.12, 2001:500:2::c	Cogent Communications
d.root-servers.net	199.7.91.13, 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

DNS hierarchy: Root servers delegate each TLD to separate servers, which delegate each second-level domain, etc.

Name Resolution

Application Defines how individual applications communicate



1. Where is **www.cnn.com**?

ISP's recursive DNS server

9. **www.cnn.com** is at 151.101.67.5

10. Added to client's cache: "**www.cnn.com** is at 151.101.67.5"

8. Added to DNS server's cache: "**www.cnn.com** is at 151.101.67.5"

2. Where is **www.cnn.com**?

3. Answers for **com** are at com nameserver.

4. Where is **www.cnn.com**?

5. Answers for **cnn.com** are at cnn.com nameserver.

6. Where is **www.cnn.com**?

7. **www.cnn.com** is at 151.101.67.5

root DNS server

com DNS server

cnn.com DNS server

DNS servers and clients cache responses to avoid extra lookups.

Each record has a **time-to-live (TTL)**, set by authoritative server.

Decremented each second. When it reaches zero, record is discarded.

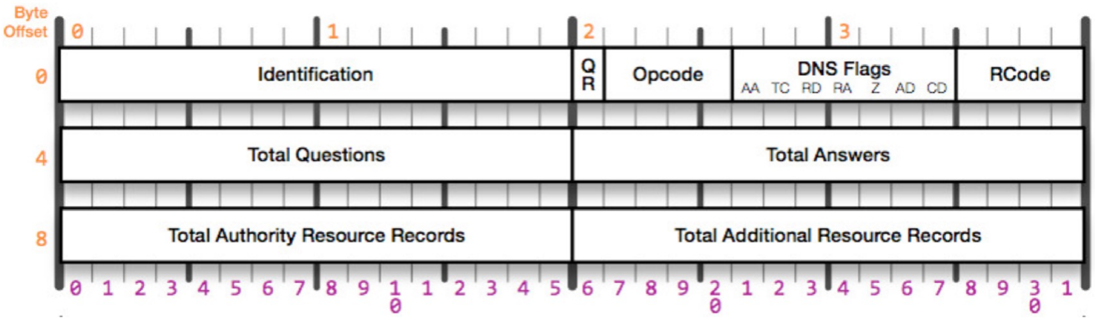
DNS Packets

Application Defines how individual applications communicate

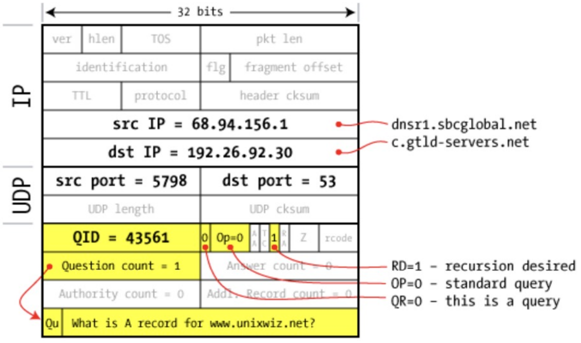
DNS (typically) uses UDP packets.

Four sections: questions, answers, authority, additional records

Identification: 16-bit random value (QID) that links response to query



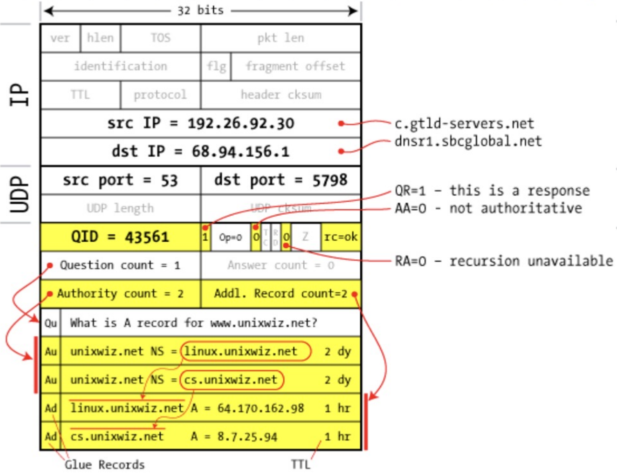
Request Packet



dnsr1.sbcglobal.net
c.gtld-servers.net

RD=1 - recursion desired
OP=0 - standard query
QR=0 - this is a query

Response Packet



c.gtld-servers.net
dnsr1.sbcglobal.net

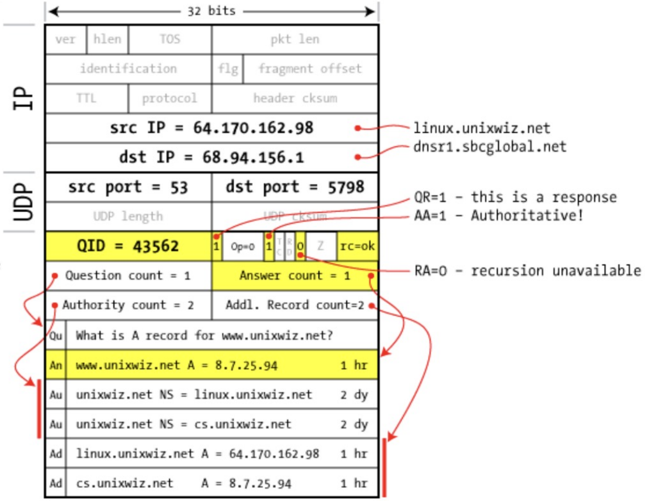
QR=1 - this is a response
AA=0 - not authoritative

RA=0 - recursion unavailable

Glue Records

TTL

Authoritative Response Packet



linux.unixwiz.net
dnsr1.sbcglobal.net

QR=1 - this is a response
AA=1 - Authoritative!

RA=0 - recursion unavailable

You'll experiment with DNS packets in Project 3.

Attacking DNS

Application Defines how individual applications communicate

DNS compromise allows MITM attacks.

An attacker who subverts DNS can return malicious responses that direct clients to visit attacker’s server in place of real server.

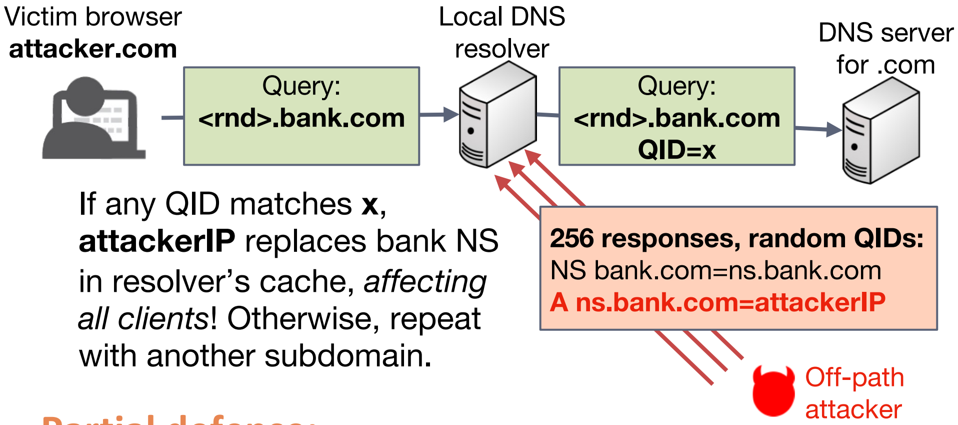
Examples of DNS attacks:

- **DNS hijacking**: Attacker hacks into home router, changes DHCP settings to point clients to attacker-controller DNS server…
- **Hosts file hijacking**: Malware edits OS `hosts` file to redirect target sites to malicious server.
- **DNS monitoring** and **DNS blocking**: ISP monitors DNS requests to track users. Injects fake responses to block censored sites.

Off-path DNS cache poisoning

Attack discovered by Dan Kaminsky in 2008.

DNS authenticates responses with 16-bit QueryID. Valid responses may include names not requested, if same DNS server controls them (“in bailiwick”)…



If any QID matches **x**, **attackerIP** replaces bank NS in resolver’s cache, *affecting all clients*! Otherwise, repeat with another subdomain.

Partial defense:

Randomize UDP source port (16 bits of entropy).
Randomize capitalization in query (1 bit per letter).

Encrypted DNS

Application Defines how individual applications communicate

DNSSEC adds authentication and integrity to DNS responses.

- Authoritative DNS servers sign DNS responses using cryptographic key.
- Clients can verify that a response is legitimate by checking signature through PKI similar to HTTPS.
- ***Does not*** provide confidentiality. Requests and responses are plaintext.

Issue: Slow adoption by domains and resolvers. Most people don't use DNSSEC and probably never will. Need other defenses.

DNS-over-TLS and DNS-over-HTTPS operate DNS over an encrypted channel.

- DNS packets, but using TLS or HTTPS as transport layer instead of plaintext UDP.
- Also JSON: https://dns.google/query?name=eecs388.org
- Provides confidentiality and integrity for connection from client to DNS server.
- ***Does not*** guarantee results authenticated. Server's onward queries to authoritative servers may fall back to UDP.

Chrome and Firefox now use encrypted DNS where available. However, by default they fall back to UDP when encrypted DNS is blocked…***allows downgrade attacks.***

Coming Up

Reminders:

Web Project due Today at 6 PM

Midterm Exam, Friday, Oct 18, 7–8:30 PM.

Next week:

Network Defense

Denial of service attacks; firewalls, IDSes, VPNs, zero trust

Authentication & Passwords

Passwords, online and offline guessing