CS 772/872: **Advanced**

Computer and Network Security

Fall 2025

Course Link:

https://shhaos.github.io/courses/CS872/netsec-fall25.html

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OLD DOMINION UNIVERSITY

CS 772/872: Advanced Computer and Network Security

- **Network Security** (including Crypto foundations and applications)
- **Web and Browser Security**
- **Cloud Security**
- **System/Software Security**
- **AI/LLM Security** (by papers)

Network Security

- TCP/IP
- DNS
- BGP
- (D)DoS Attacks
- CDN

- Applied Cryptography
- PKI
- SSL/TLS and HTTPS
- DNSSEC/RPKI

Network Security

- **Confidentiality**: only sender, intended receiver should "understand" message contents
  - sender encrypts message
  - receiver decrypts message
- **Integrity**: sender, receiver want to ensure message not altered (in transit, or afterwards)
- **Authentication**: sender, receiver want to confirm identity of each other

Network Security

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  - sender encrypts message
  - receiver decrypts message
- **Integrity**: sender, receiver want to ensure message not altered (in transit, or afterwards)
- **Authentication**: sender, receiver want to confirm identity of each other
- **Accessibility and Availability**: services must be accessible and available to users

Network Security

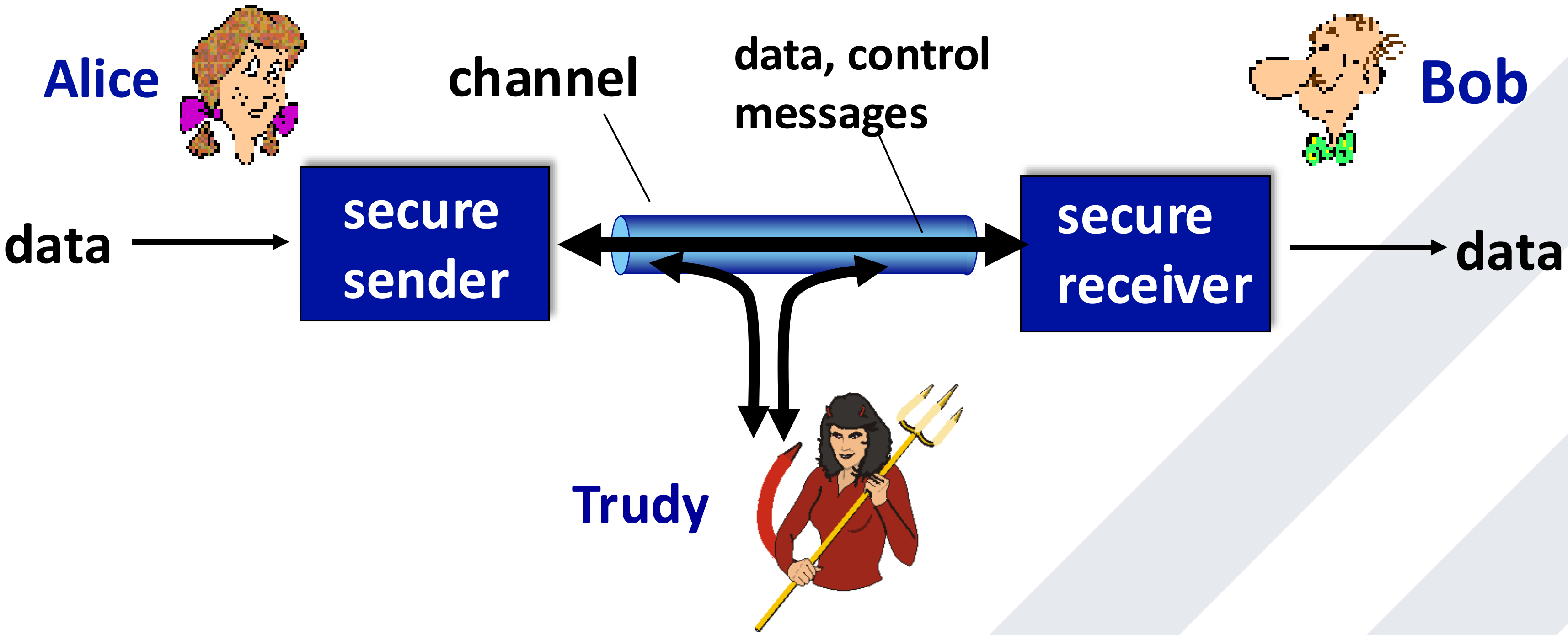
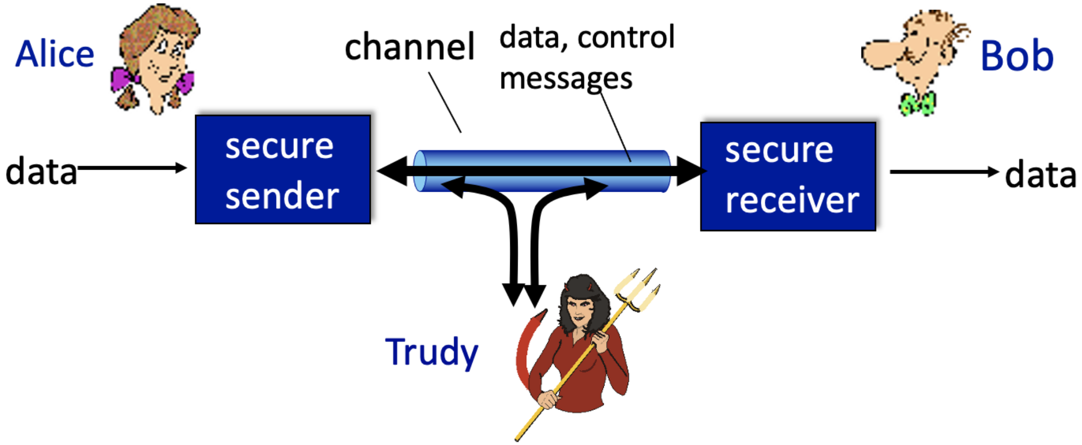


Image: Computer Networking: A Top Down Approach, J. Kurose and K. Ross

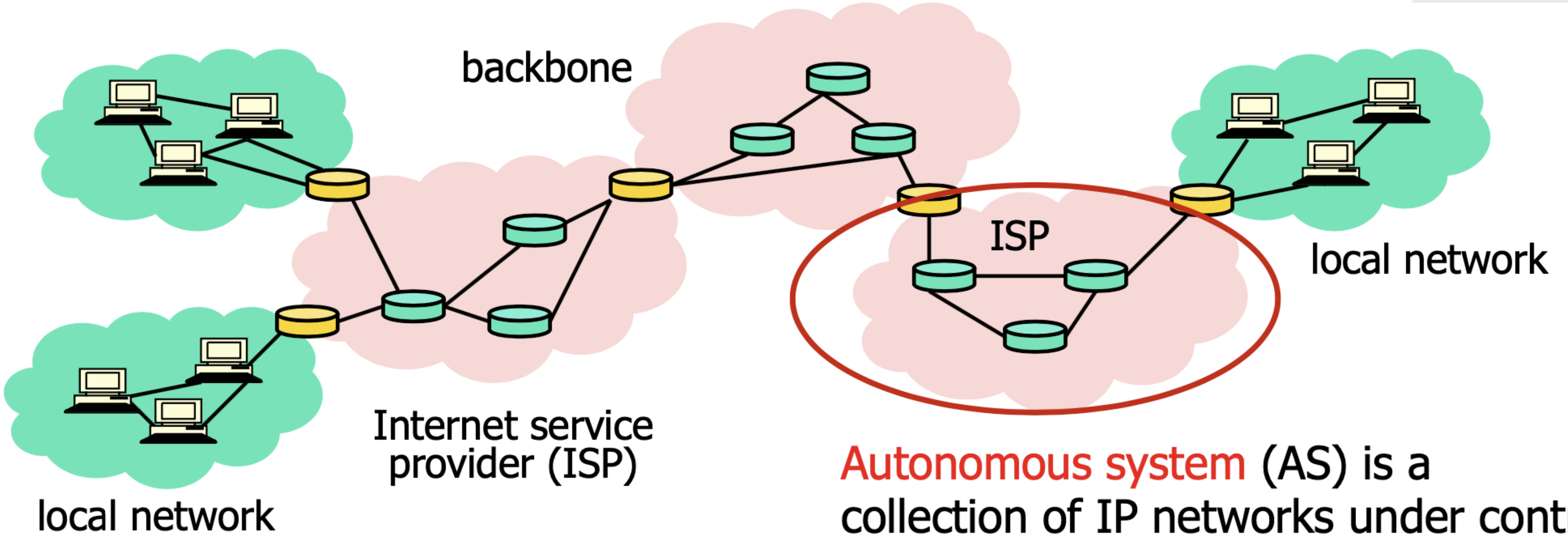
Network Security

- **Eavesdrop**: Intercept messages
- **Impersonation**: fake/spoof source address of packets
- **Hijacking**: “take over” ongoing connection by inserting himself in place
- **Denial of service**: prevent service from being used by others



Network Security

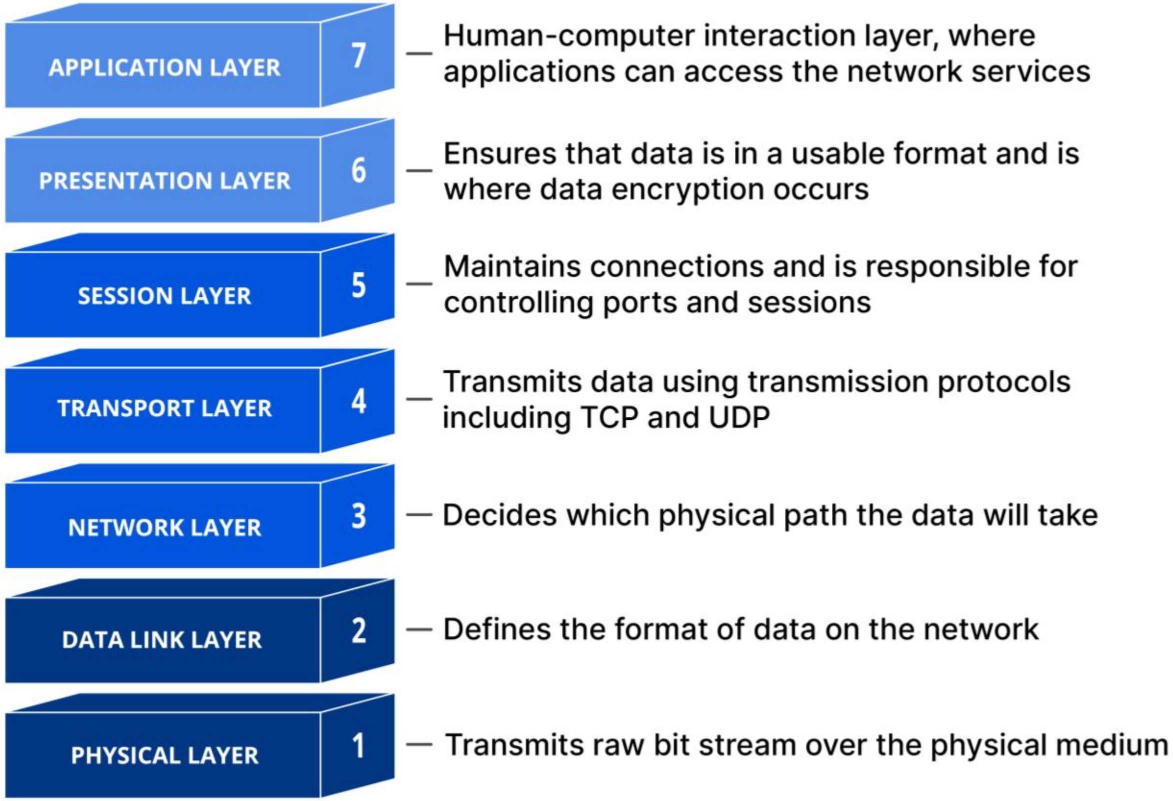
- **Internet: a Network of Network**



Autonomous system (AS) is a collection of IP networks under control of a single administrator (e.g., ISP)

Network Security

- OSI Protocol Stack



APPLICATION LAYER 7 — Human-computer interaction layer, where applications can access the network services

PRESENTATION LAYER 6 — Ensures that data is in a usable format and is where data encryption occurs

SESSION LAYER 5 — Maintains connections and is responsible for controlling ports and sessions

TRANSPORT LAYER 4 — Transmits data using transmission protocols including TCP and UDP

NETWORK LAYER 3 — Decides which physical path the data will take

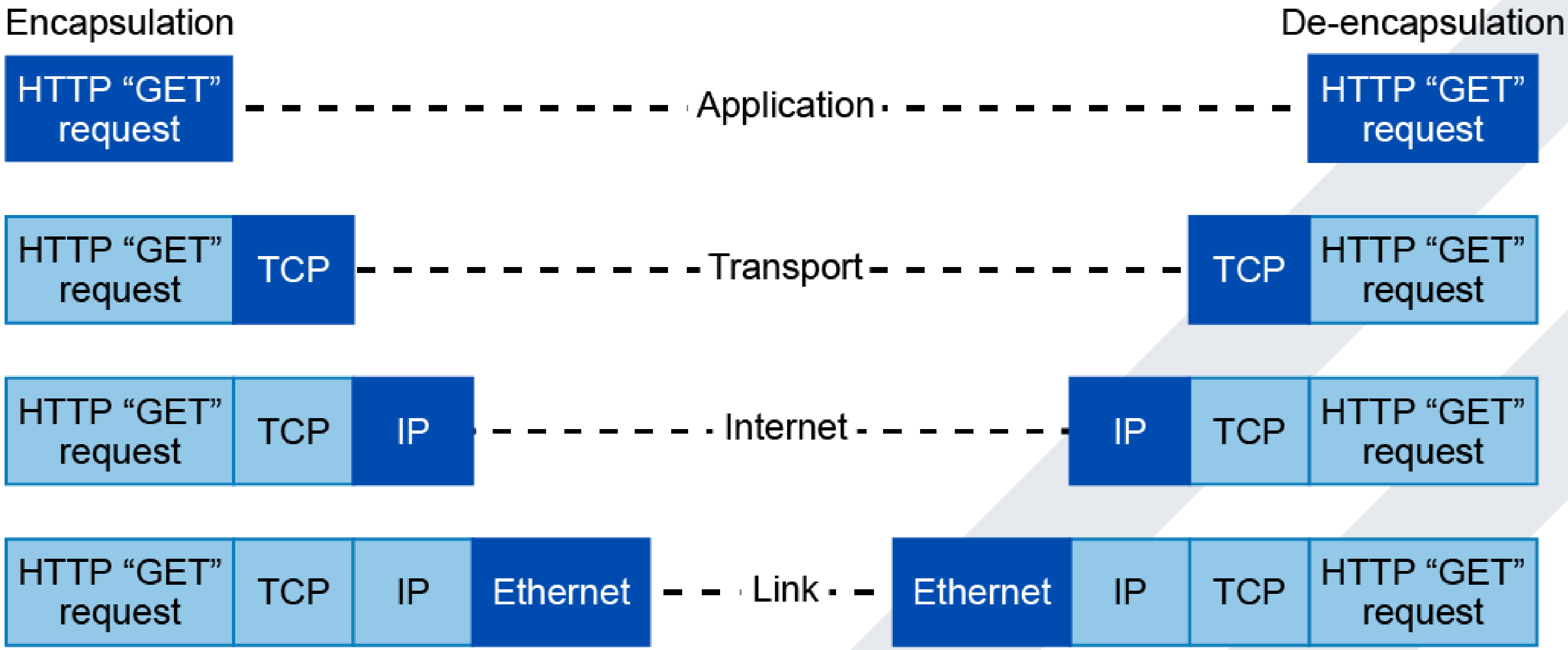
DATA LINK LAYER 2 — Defines the format of data on the network

PHYSICAL LAYER 1 — Transmits raw bit stream over the physical medium

Image: Cloudflare

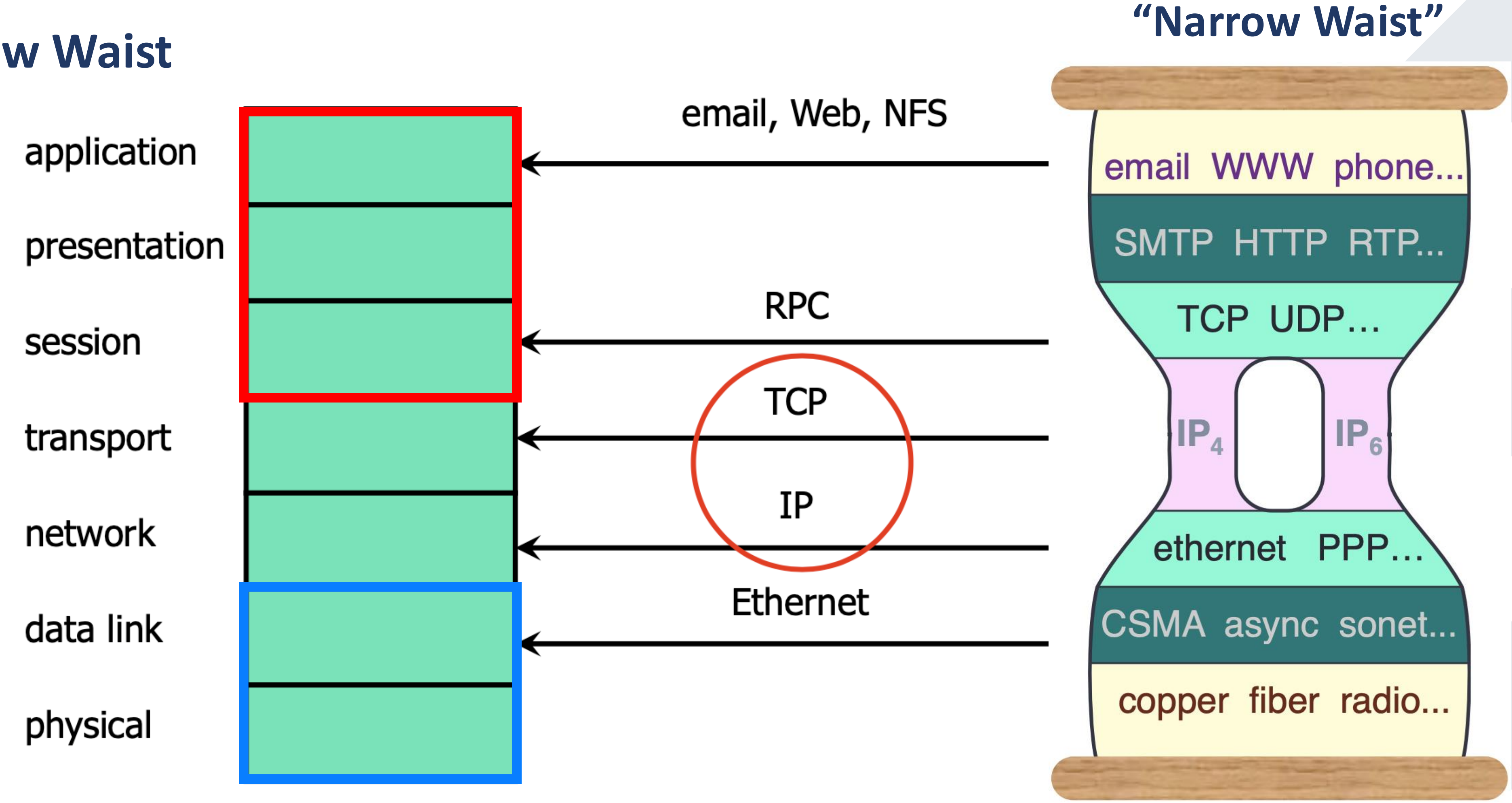
Network Security

- **Encapsulation: end-to-end connectivity**



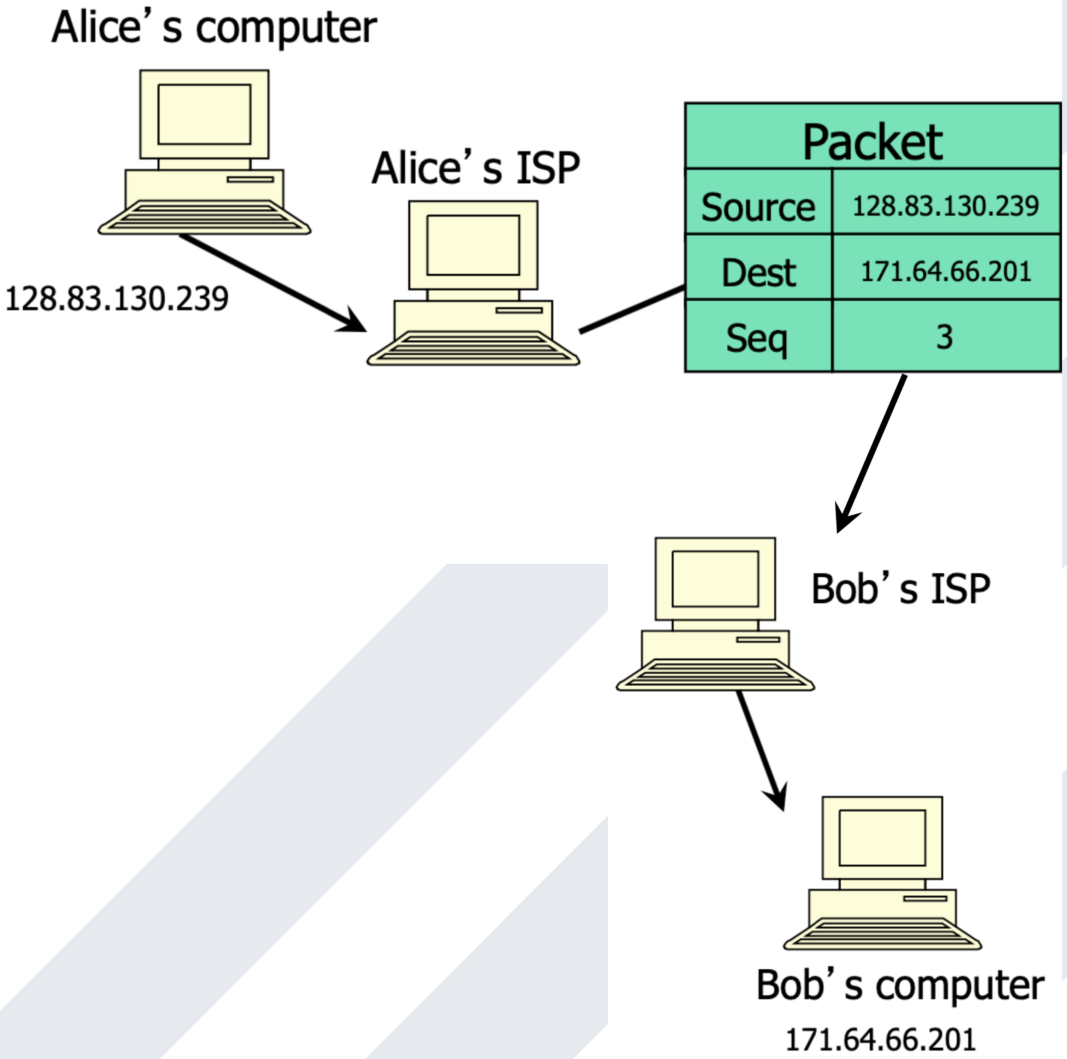
Network Security

- Narrow Waist



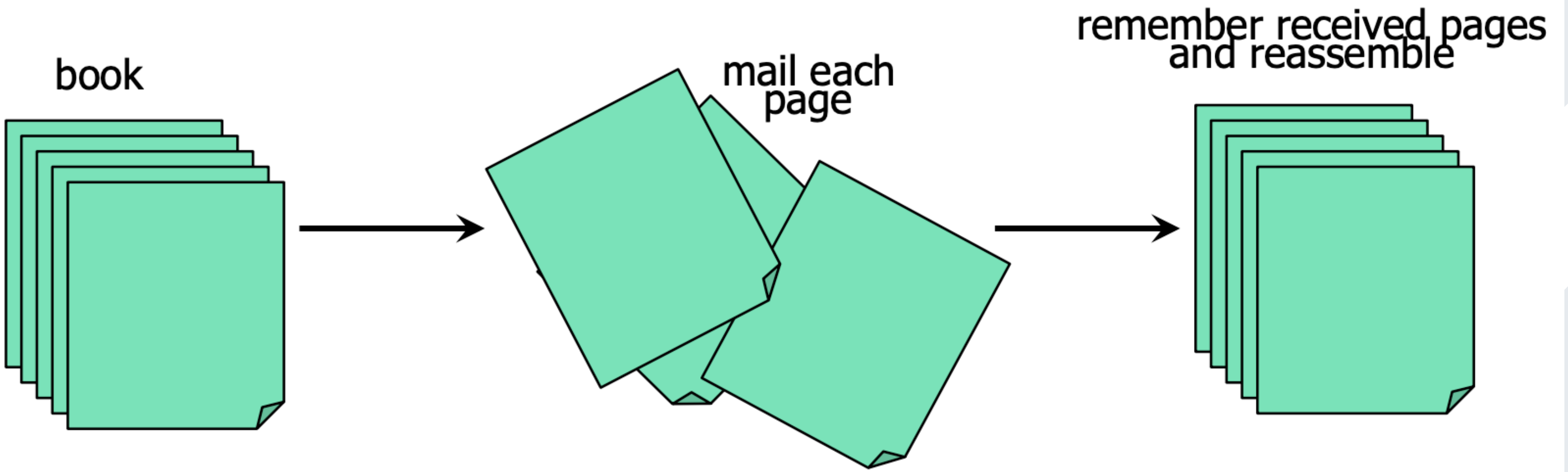
IP – Internet Protocol

- **Connectionless**
  - Unreliable, “best-effort” protocol
- **Packet switching**
  - No states established ahead of time
  - Destination-based Routing
  - Shared resources



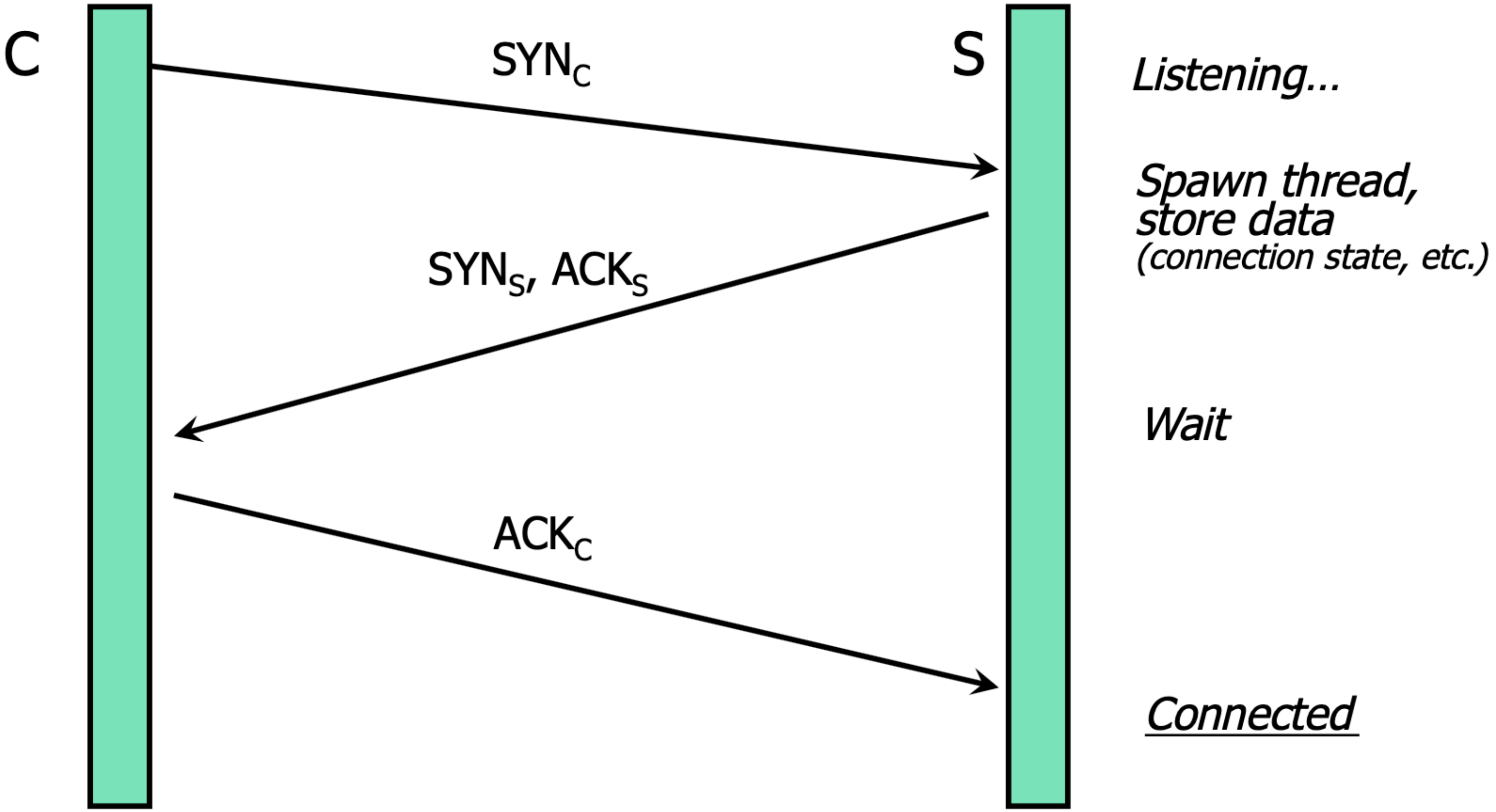
TCP – Transmission Control Protocol

- **Sender: break data into segments**
  - Sequence number is assigned to every segment
- **Receiver: reassemble segments in correct order**
  - Acknowledge receipt; lost segments will be re-sent
- **Connection state maintained on both sides**



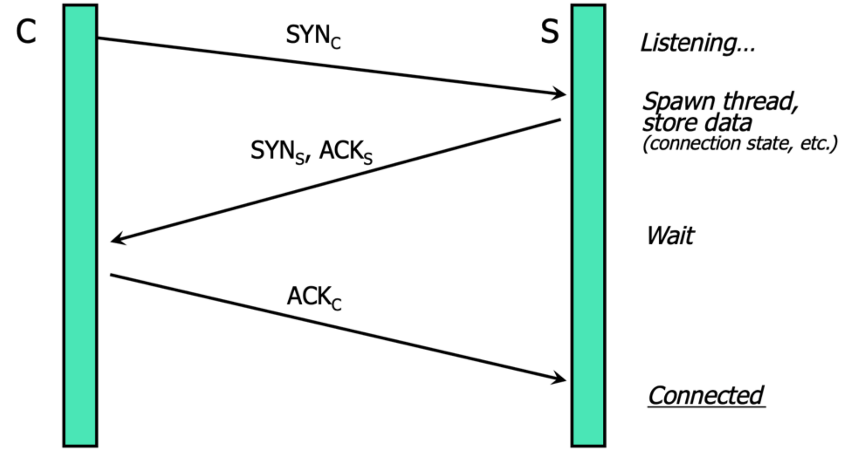
TCP – Transmission Control Protocol

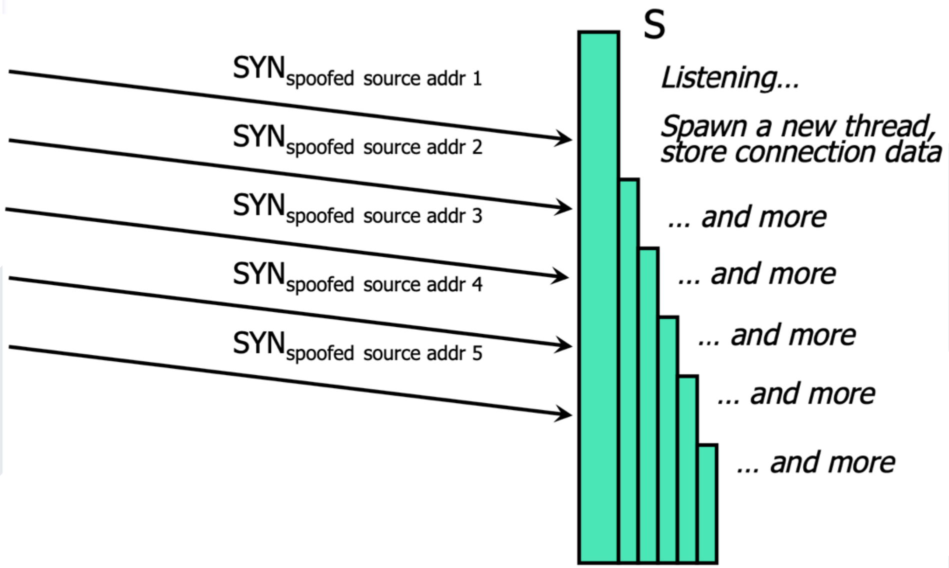
- **TCP Handshake: Connection establishment**



TCP – Transmission Control Protocol

- **SYN Flooding Attack**
  - Attacker sends many connection requests with spoofed source address
  - Victim allocates resources for each request
    - New thread
    - “half-open” connections
  - Once resources exhausted, legitimate requests are dropped
  - **Classic (Distributed-)Denial-of-Service (DDoS) pattern**



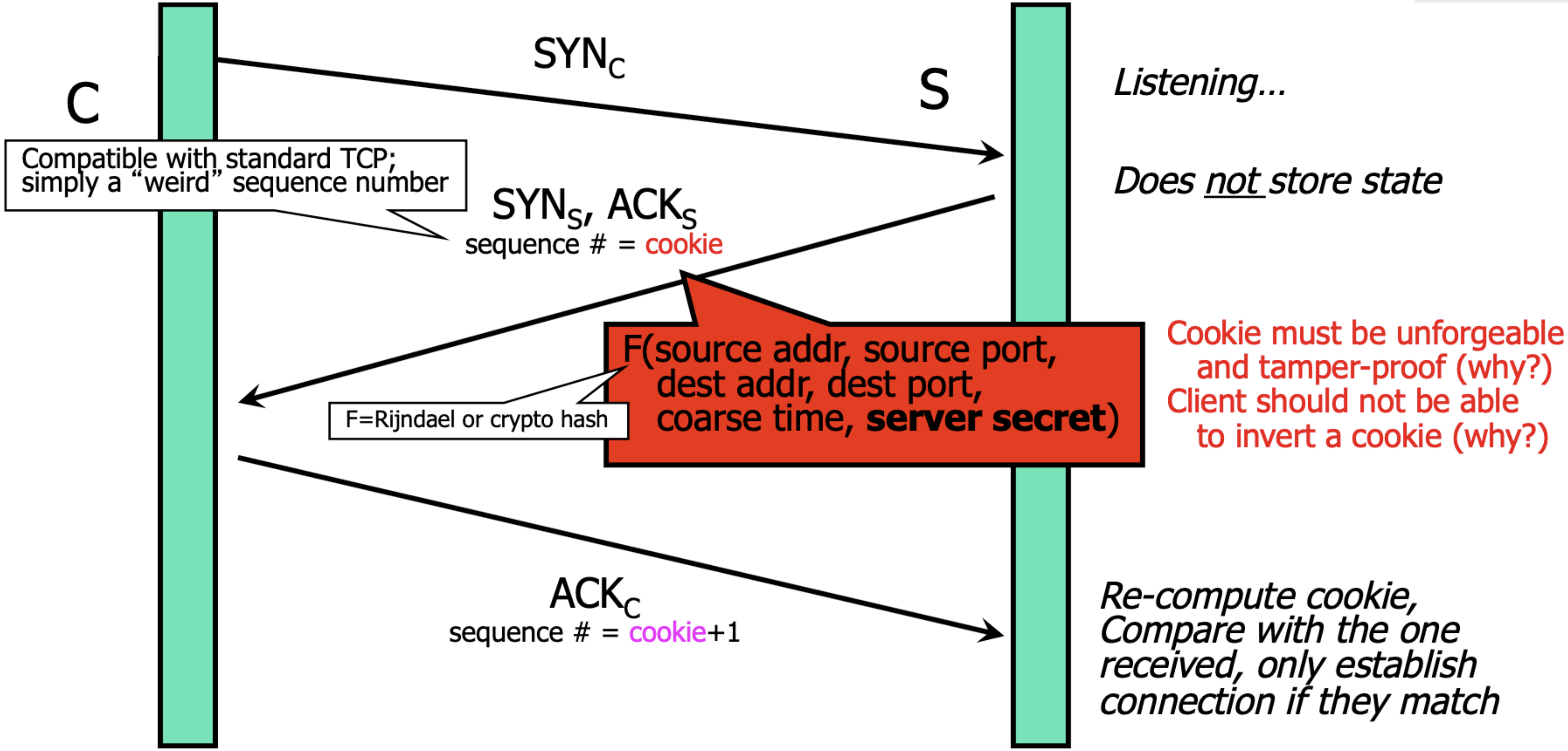

S
$SYN_{spoofed\ source\ addr\ 1}$
$SYN_{spoofed\ source\ addr\ 2}$
$SYN_{spoofed\ source\ addr\ 3}$
$SYN_{spoofed\ source\ addr\ 4}$
$SYN_{spoofed\ source\ addr\ 5}$
Listening...
Spawn a new thread, store connection data
... and more
... and more
... and more
... and more
... and more

TCP – Transmission Control Protocol

- **Preventing Denial of Service**
  - DoS is caused by asymmetric state allocation
    - If a victim server opens new state for each connection attempt, attacker can initiate thousands of connections from bogus or forged IP addresses
  - Cookies ensure that the responder (victim) is stateless until initiator produced at least one acknowledgment
    - Responder’s state (IP addresses and ports of the connection) is stored in a cookie and sent to initiator
    - After initiator responds, cookie is regenerated and compared with the cookie returned by the initiator

TCP – Transmission Control Protocol

- **Preventing Denial of Service**


C
S
SYN_C
Listening…
Compatible with standard TCP; simply a "weird" sequence number
SYN_S, ACK_S
sequence # = cookie
Does *not* store state
F(source addr, source port, dest addr, dest port, coarse time, **server secret**)
F=Rijndael or crypto hash
ACK_C
sequence # = cookie+1

Cookie must be unforgeable and tamper-proof (why?)
Client should not be able to invert a cookie (why?)

Re-compute cookie, Compare with the one received, only establish connection if they match

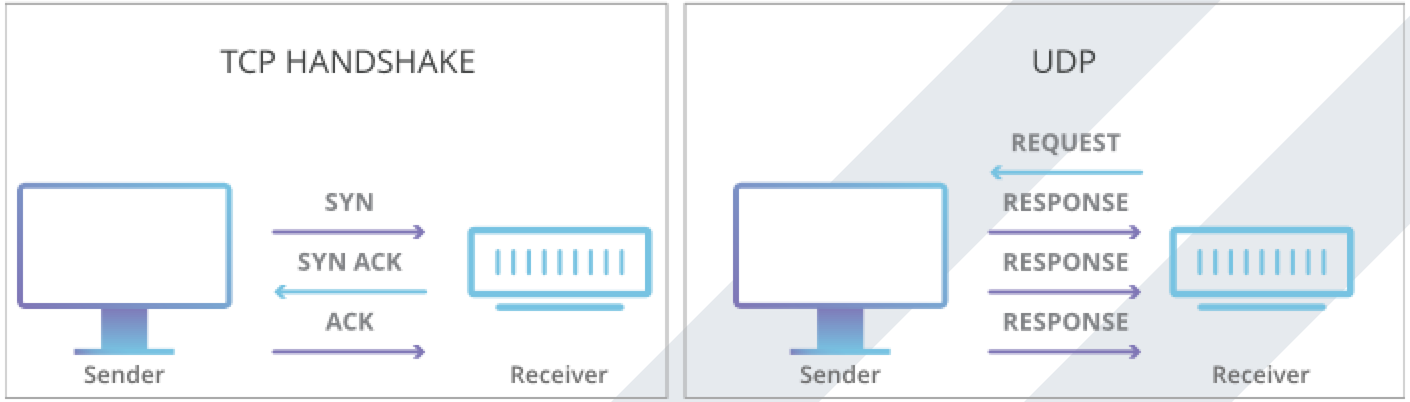
TCP – Transmission Control Protocol

- **Denial of Service by Connection Reset**
  - If attacker can guess/predict/monitor the current sequence number for an existing connection, can send RESET packet to close it
    - Especially effective against long-lived connection
  - Widely used in Internet Censorship

UDP – User Datagram Protocol

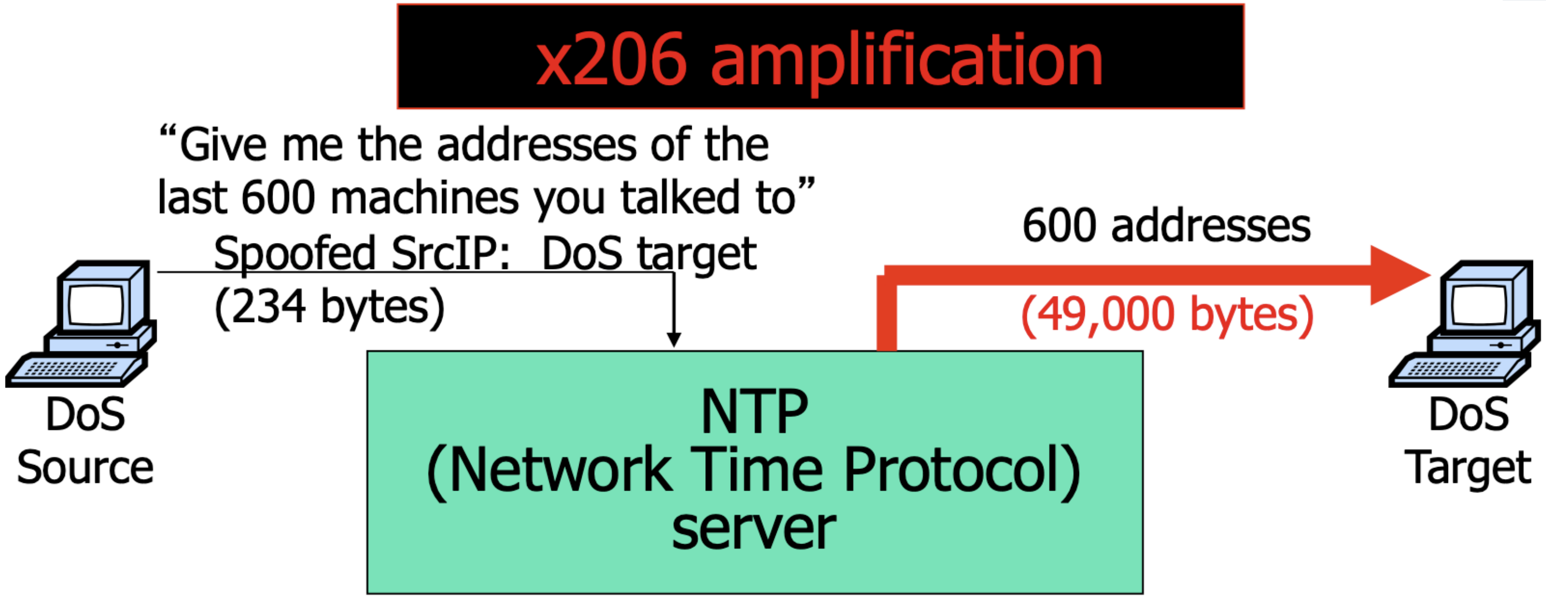
- **Connectionless protocol**
  - Simply send datagram to application process at the specified port of the IP address
  - Source port number provides return address
  - Applications: media streaming, broadcast
- **No acknowledgement, no flow control, no message continuation**

TCP vs UDP Communication



UDP – User Datagram Protocol

- **NTP Amplification Attack**
  - “Reflection-and-Amplification” attack


x206 amplification
“Give me the addresses of the last 600 machines you talked to”
Spoofed SrcIP: DoS target
(234 bytes)
600 addresses
(49,000 bytes)
DoS Source
NTP (Network Time Protocol) server
DoS Target

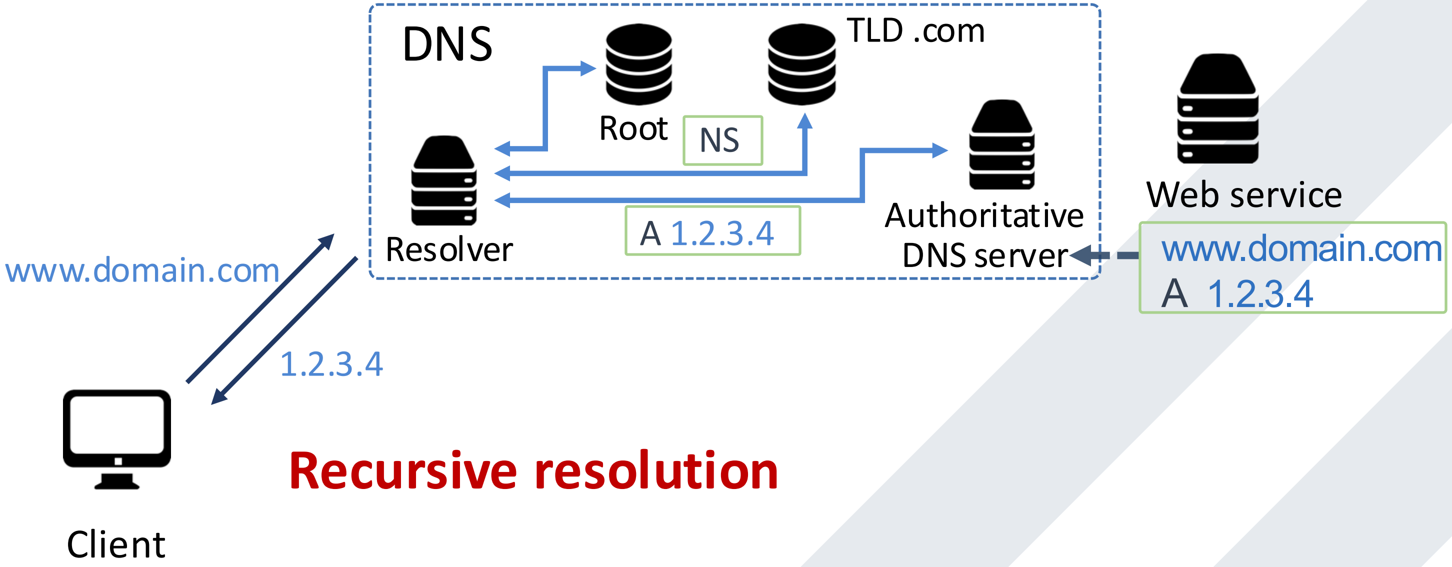
- Dec. 2013 – Feb. 2014: 400Gbps DDoS attacks involving 4,500+ NTP servers targeting Cloudflare’s data center

Network Defenses

- **Rate-limiting**
  - Straightforward but cannot differentiate legitimate traffic from malicious traffic
- **Egress Filtering against IP spoofing**
  - ISPs are lack of motivation to deploy
- **DDoS Protection Service offered by Content Delivery Networks (CDNs)**
  - Re-route the traffic to CDN’s highly distributed network infrastructures
  - Must hide the the origin IP address

DNS – Domain Name System

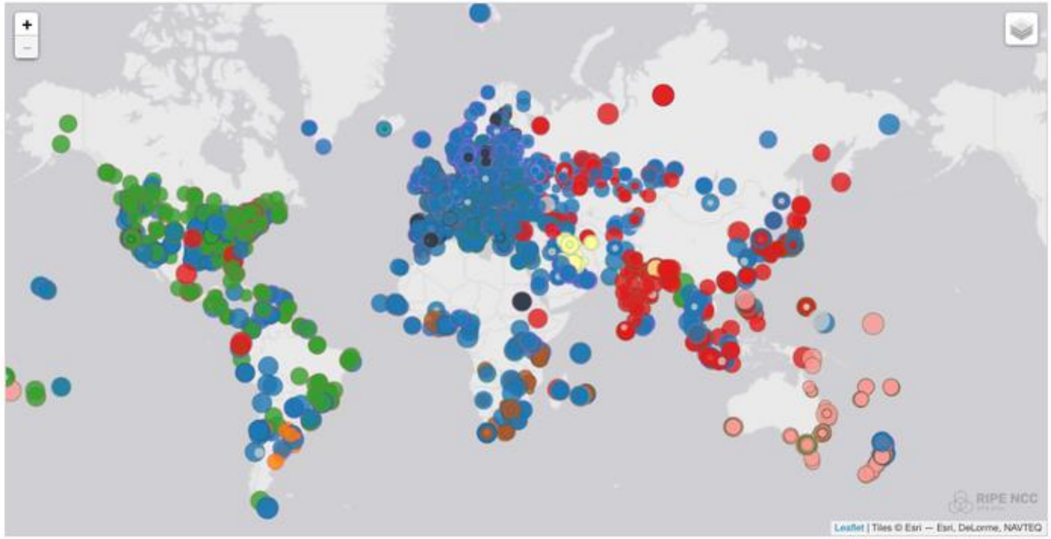
- **Internet Dictionary**
  - Maps symbolic names to numeric IP addresses
  - UDP-based protocol



Recursive resolution

DNS – Domain Name System

- **Hierarchical System Design**
  - Root nameservers for top-level domains (`.com`, `.edu`, `.uk`, etc.)
  - 13 root server systems (A - M)
  - Top-level domain (TLD) nameservers indicate authoritative nameservers
  - Authoritative nameservers (ADNS) resolve subdomains
  - Local resolvers contact authoritative servers for requested domains



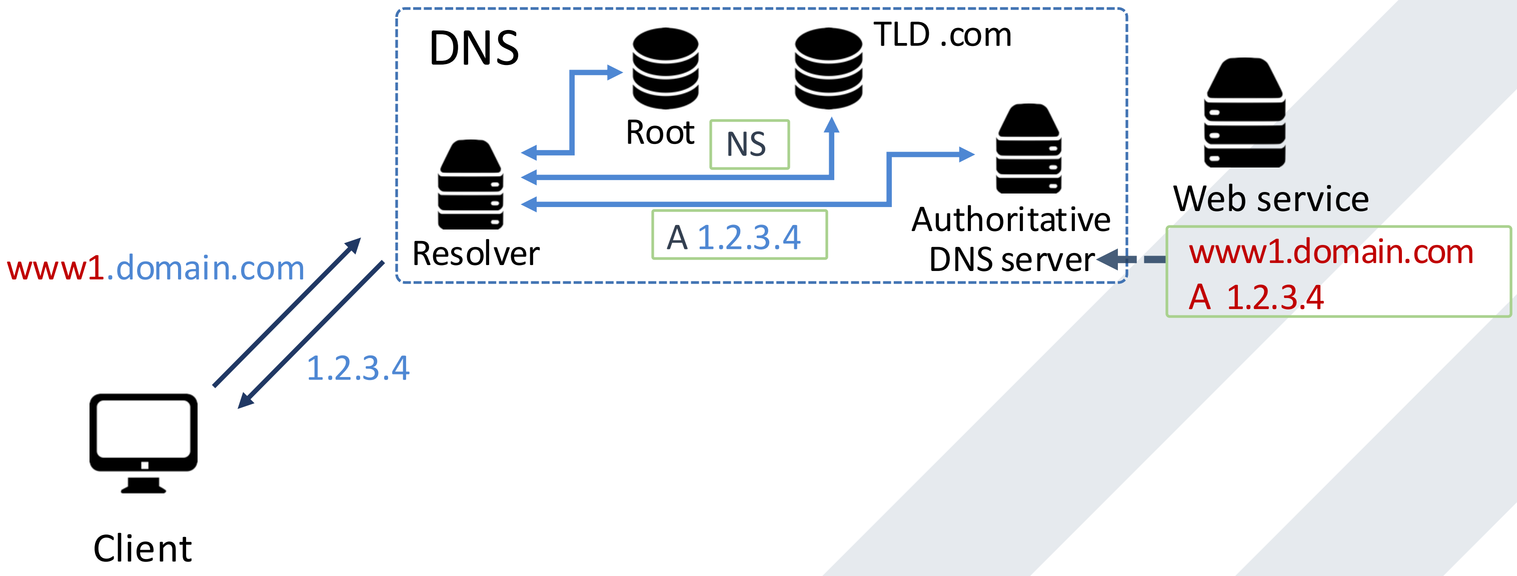
K-root servers

DNS – Domain Name System

- **DNS Caching**
  - DNS responses can be cached (on local resolvers)
    - Quick response for repeated translations
    - Other queries may reuse some parts of lookup
      - NS records identify name servers responsible for a domain
  - DNS negative queries can be cached
    - Don’t have to repeat past mistakes (failed domains, misspellings, etc.)
  - Cached data will periodically time out
    - Lifetime (TTL) of data controlled by owner of data, passed with every record

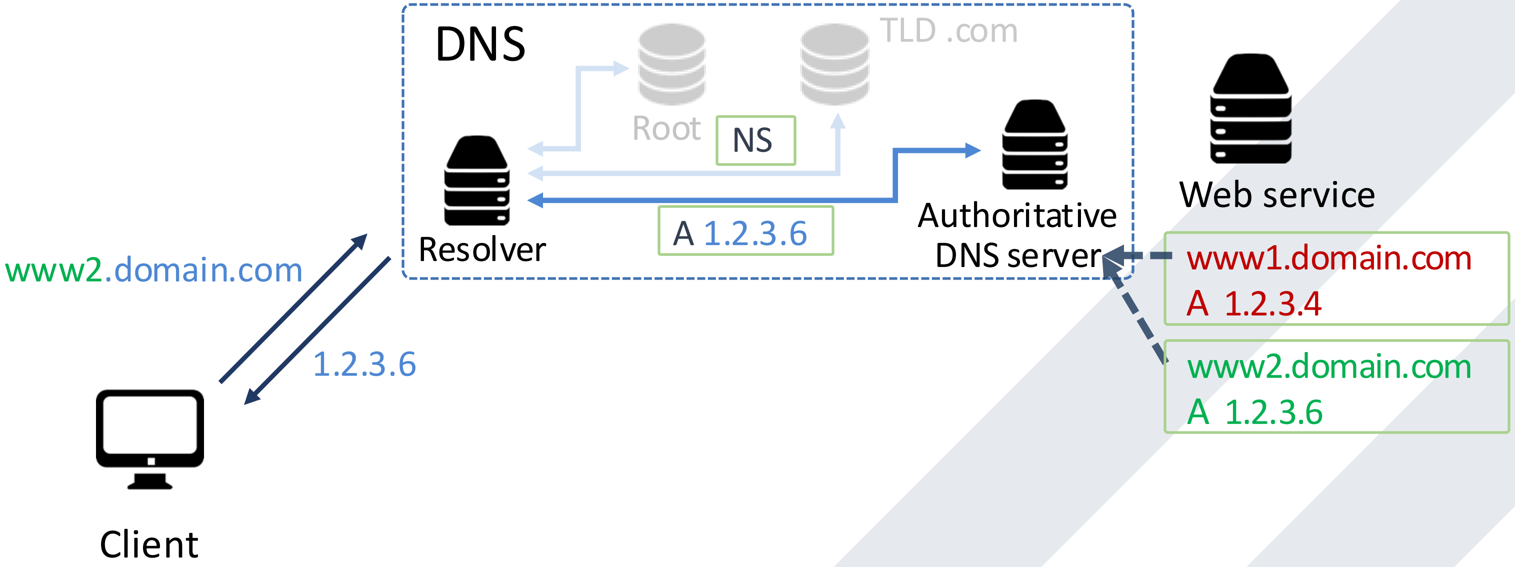
DNS – Domain Name System

- **DNS Caching**



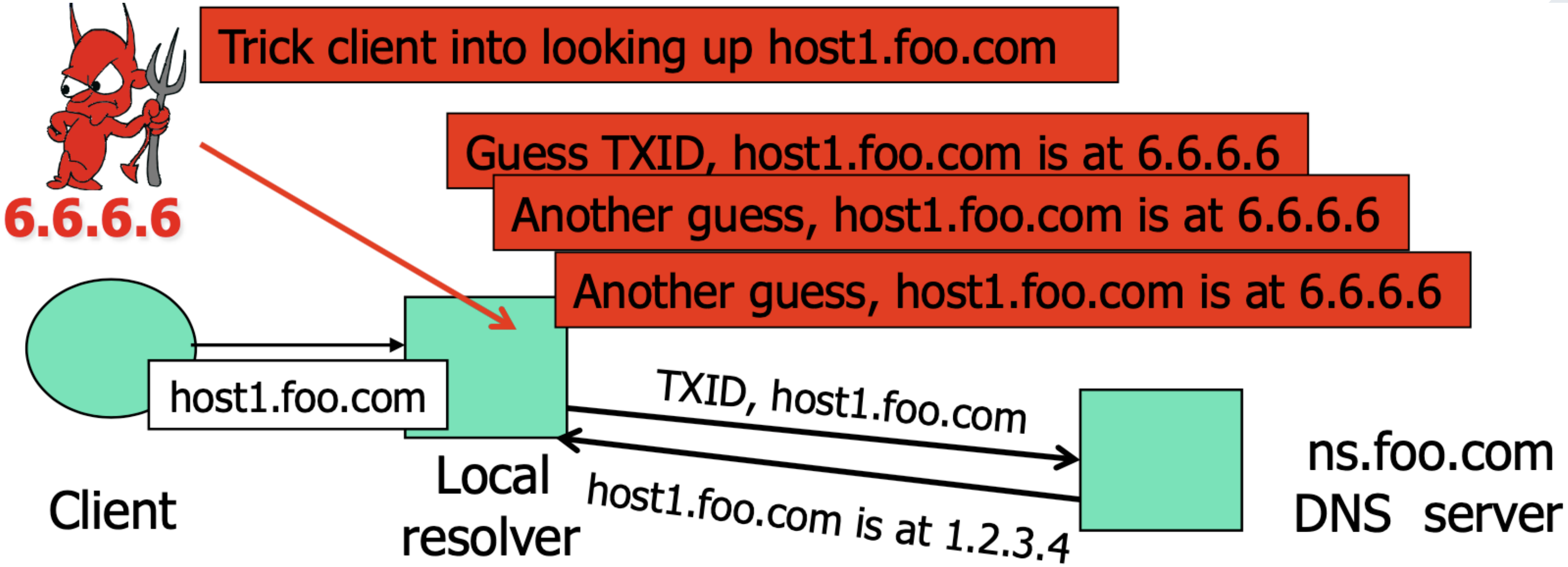
DNS – Domain Name System

- **DNS Caching**



DNS – Domain Name System

- **DNS Cache Poisoning**

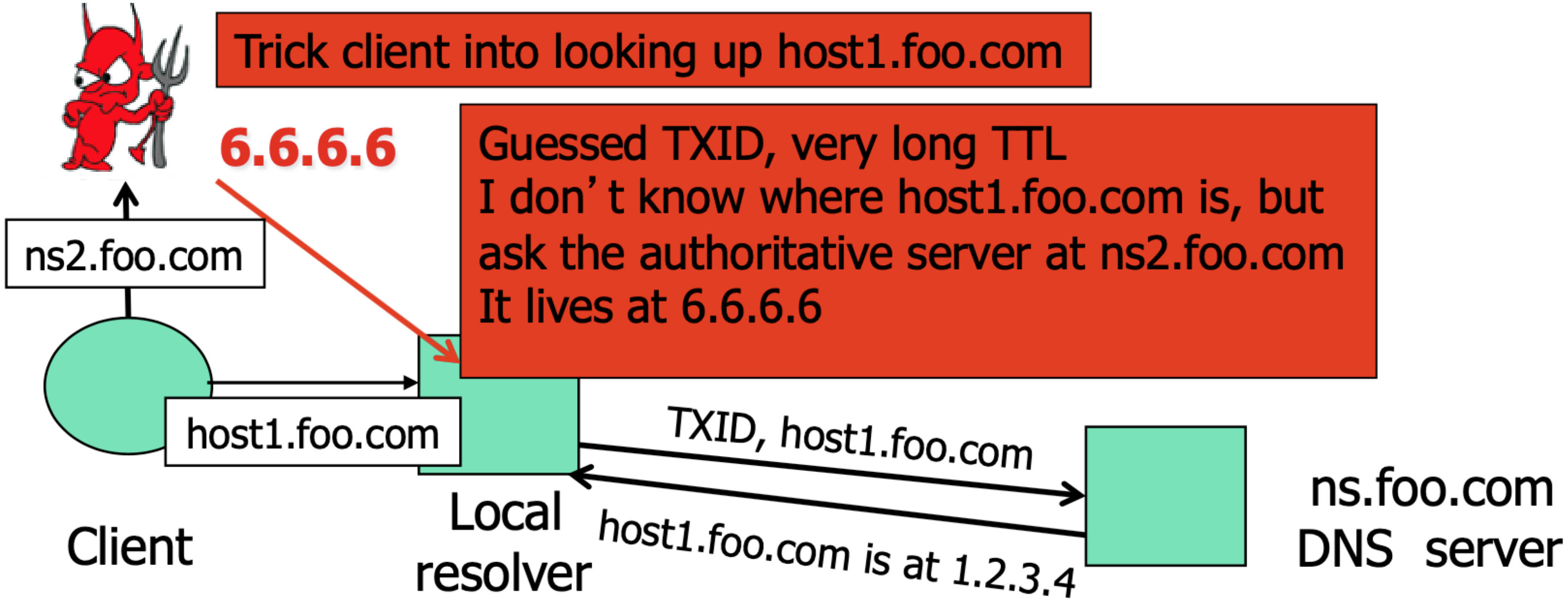


Trick client into looking up host1.foo.com
Guess TXID, host1.foo.com is at 6.6.6.6
Another guess, host1.foo.com is at 6.6.6.6
Another guess, host1.foo.com is at 6.6.6.6
6.6.6.6
host1.foo.com
TXID, host1.foo.com
Client
Local resolver
host1.foo.com is at 1.2.3.4
ns.foo.com DNS server

  - Several opportunities to win the race.
  - Here attacker attempts to pollute individual A records

DNS – Domain Name System

- **DNS Cache Poisoning – Kaminsky attack**



Trick client into looking up host1.foo.com

Guessed TXID, very long TTL
I don't know where host1.foo.com is, but
ask the authoritative server at ns2.foo.com
It lives at 6.6.6.6

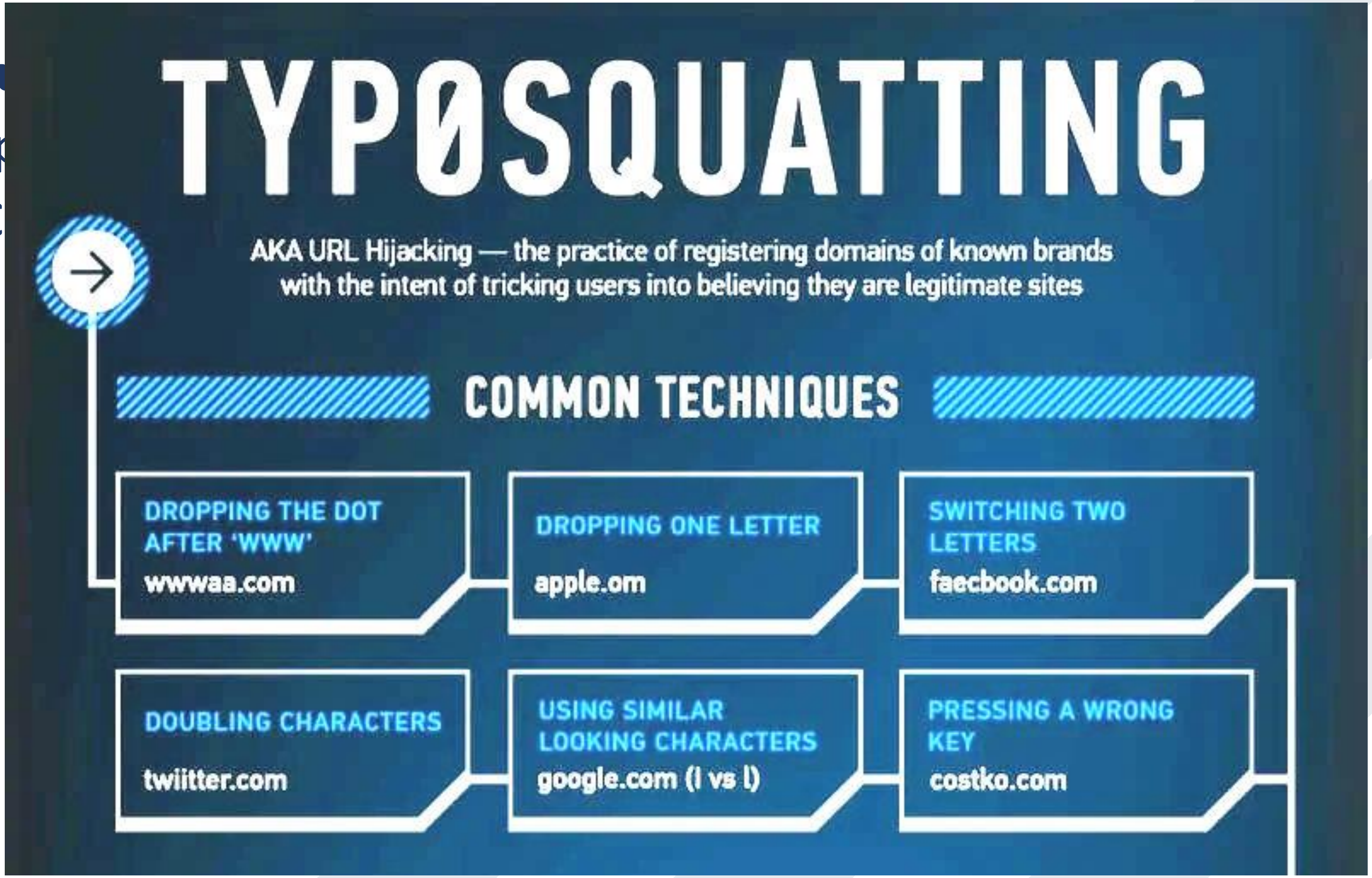
  - If win the race, any request for `<XXX>.foo.com` will go to 6.6.6.6. The NS record is poisoned for a very long time
  - If lose, try again with `<ANYTHING>.foo.com`

DNS – Domain Name System

- **Defending the DNS Cache Poisoning Problem**
  - Long TTL for legitimate responses?
    - Does it really help?
  - Randomized Transaction ID (TXID – 16 bits)
  - Randomize port in addition to TXID
    - 32 bits of randomness, makes it harder for attacker to guess TXID+port
  - **DNSSEC**
    - **Cryptographic authentication of host-address mappings**

DNS – Domain Name System

- **Other DNS-related Secu**
  - Fast flux in DNS map
    - DNS-based C&C
  - DNS squatting
    - typo-squatting,



TYPØSQUATTING

AKA URL Hijacking — the practice of registering domains of known brands with the intent of tricking users into believing they are legitimate sites

COMMON TECHNIQUES

DROPPING THE DOT AFTER 'WWW'
wwwaa.com

DROPPING ONE LETTER
apple.om

SWITCHING TWO LETTERS
faecbook.com

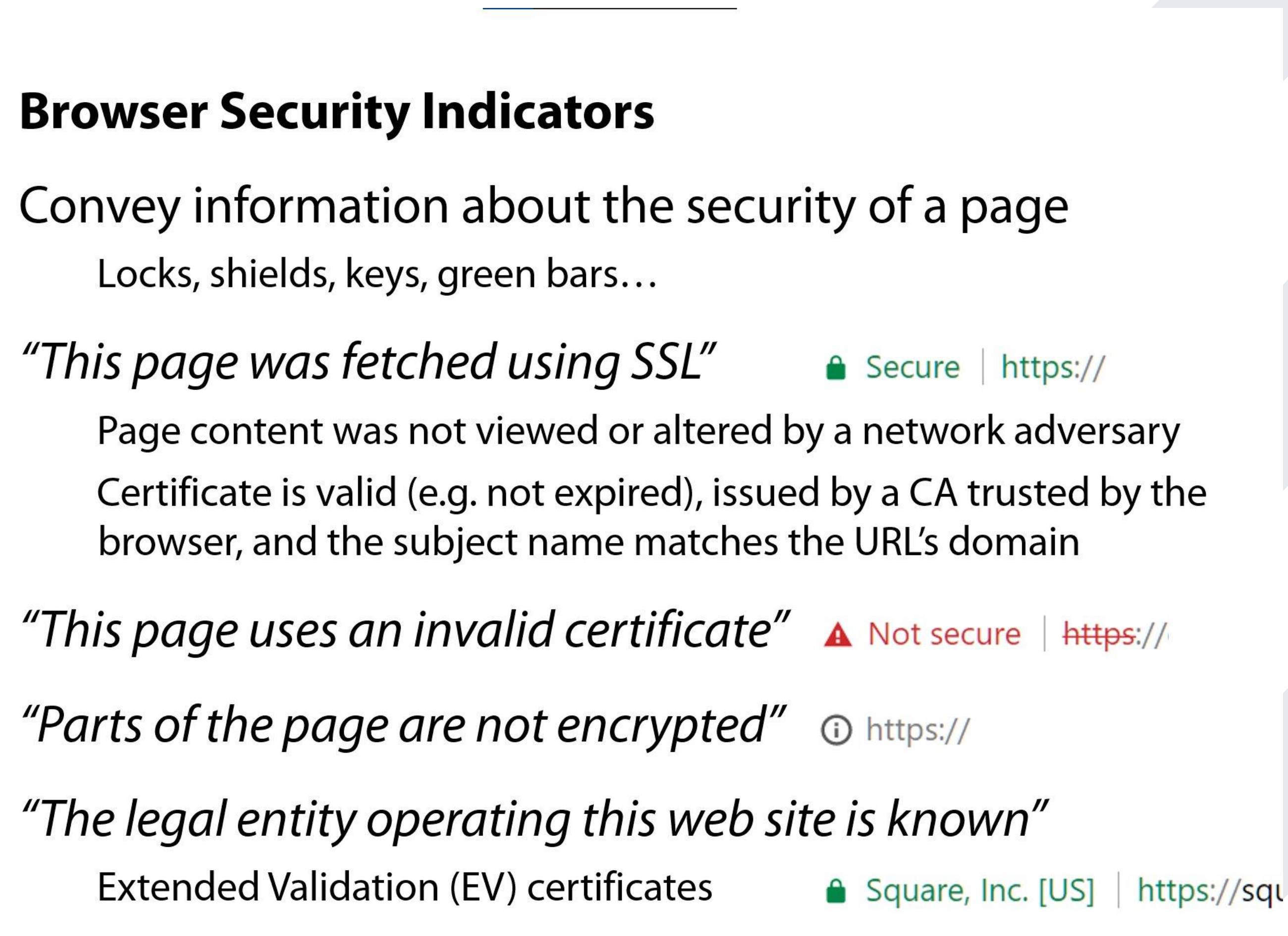
DOUBLING CHARACTERS
twiitter.com

USING SIMILAR LOOKING CHARACTERS
google.com (I vs l)

PRESSING A WRONG KEY
costko.com

DNS – Domain Name System

- **Other DNS-related Security Is**
  - Fast flux in DNS mappings
    - DNS-based C&C (Contr
  - DNS squatting
    - typo-squatting, combc



Browser Security Indicators

Convey information about the security of a page

Locks, shields, keys, green bars…

“This page was fetched using SSL” 🔒 Secure | https://

Page content was not viewed or altered by a network adversary

Certificate is valid (e.g. not expired), issued by a CA trusted by the browser, and the subject name matches the URL’s domain

“This page uses an invalid certificate” ⚠ Not secure | ~~https~~://

“Parts of the page are not encrypted” ⓘ https://

“The legal entity operating this web site is known”

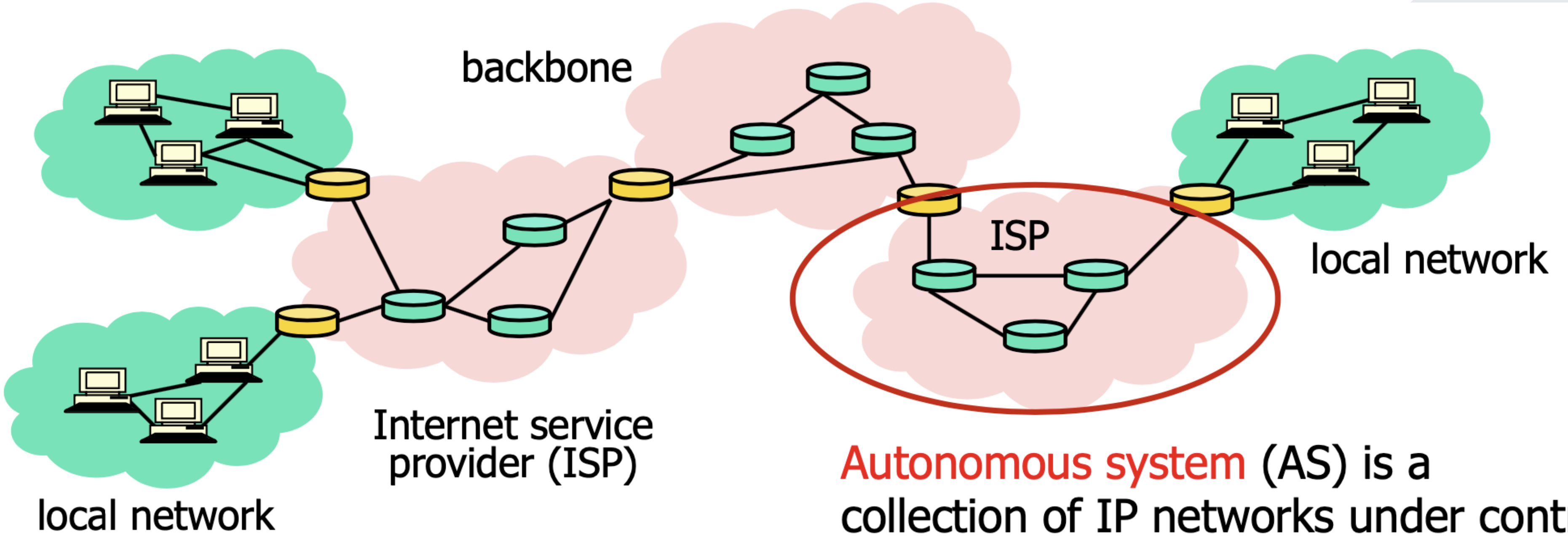
Extended Validation (EV) certificates 🔒 Square, Inc. [US] | https://squ

DNS – Domain Name System

- **Other DNS-related Security Issues**
  - Fast flux in DNS mappings
    - DNS-based C&C (Control-and-command) in botnets
  - DNS squatting
    - typo-squatting, combo-squatting
  - Domain/subdomain hijacking
    - Dangling DNS records, domain shadowing
  - DNS Amplification

IP Routing – BGP (Border Gateway Protocol)

- **Internet: a Network of Network**



Autonomous system (AS) is a collection of IP networks under control of a single administrator (e.g., ISP)

IP Routing – BGP (Border Gateway Protocol)

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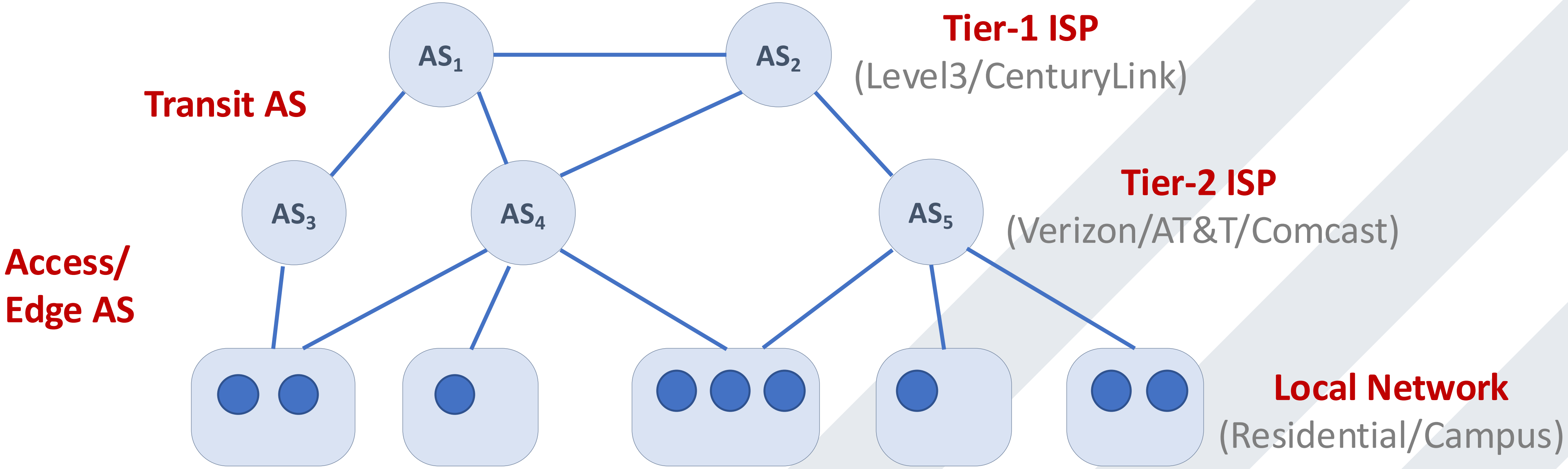

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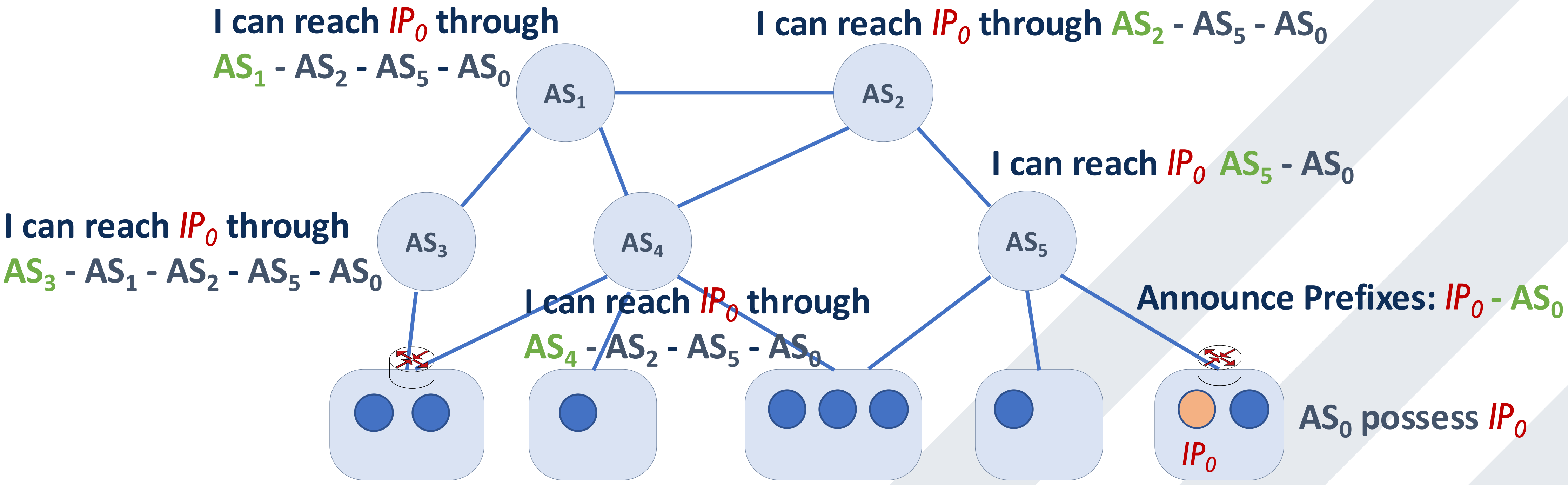

I can reach *IP_0* through AS_1 - AS_2 - AS_5 - AS_0
I can reach *IP_0* through AS_2 - AS_5 - AS_0
I can reach *IP_0* AS_5 - AS_0
I can reach *IP_0* through AS_3 - AS_1 - AS_2 - AS_5 - AS_0
I can reach *IP_0* through AS_4 - AS_2 - AS_5 - AS_0
Announce Prefixes: *IP_0* - AS_0
AS_1
AS_2
AS_3
AS_4
AS_5
IP_0
AS_0 possess *IP_0*

IP Routing – BGP (Border Gateway Protocol)

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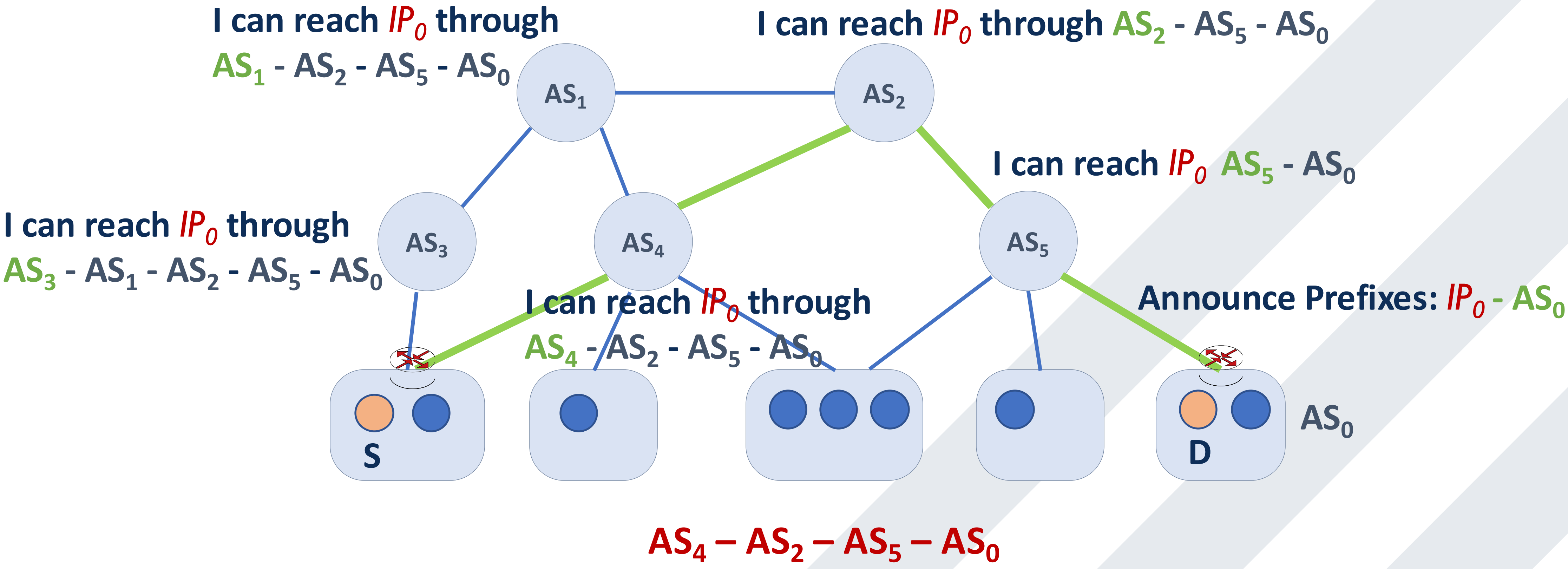

I can reach IP_0 through AS_1 - AS_2 - AS_5 - AS_0
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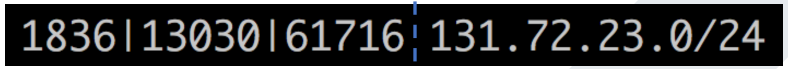
AS_1
AS_2
I can reach IP_0 AS_5 - AS_0
I can reach IP_0 through AS_3 - AS_1 - AS_2 - AS_5 - AS_0
AS_3
AS_4
AS_5
I can reach IP_0 through AS_4 - AS_2 - AS_5 - AS_0
Announce Prefixes: IP_0 - AS_0
S
D
AS_0
AS_4 – AS_2 – AS_5 – AS_0

IP Routing – BGP (Border Gateway Protocol)

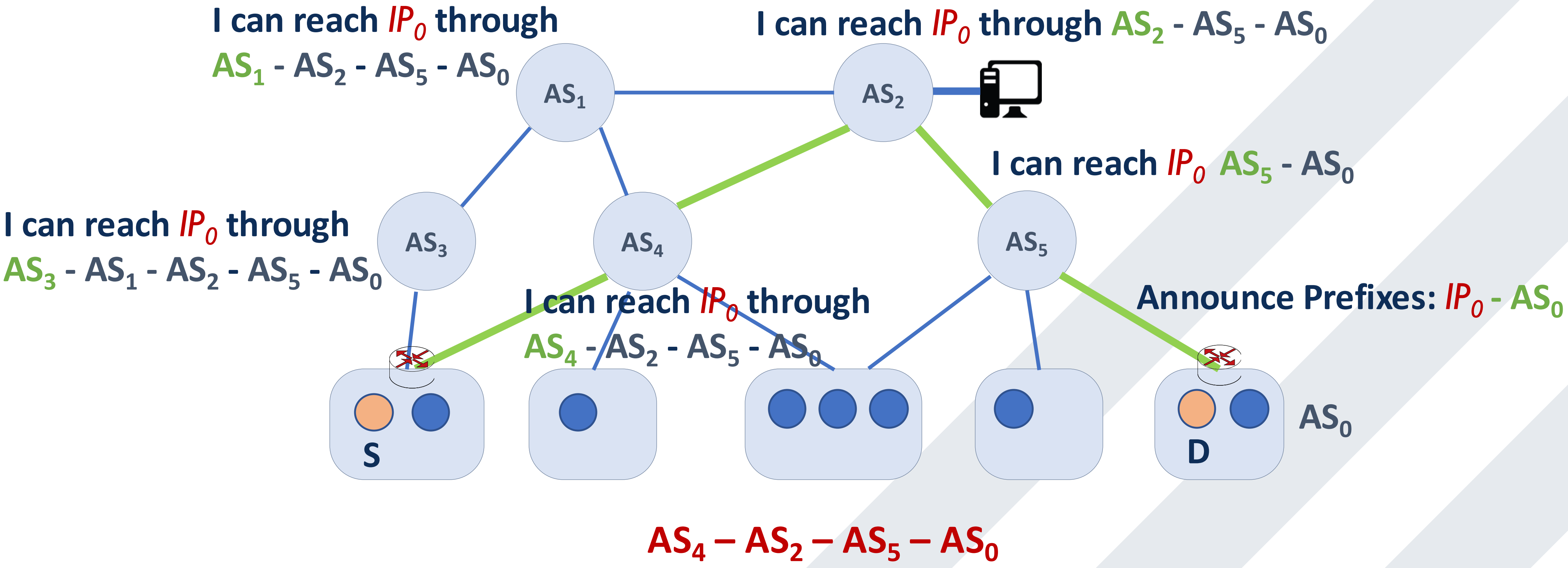
- **Internet: a Network of Network**

(Destination) Prefix



```
1836|13030|61716 131.72.23.0/24
```

Host AS | Transit AS | Origin AS



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I can reach *IP_0* AS_5 - AS_0

I can reach *IP_0* through AS_3 - AS_1 - AS_2 - AS_5 - AS_0

I can reach *IP_0* through AS_4 - AS_2 - AS_5 - AS_0

Announce Prefixes: *IP_0* - AS_0

AS_4 – AS_2 – AS_5 – AS_0

BGP (In)Security

- BGP update messages contain no authentication or integrity protection
- Attacker (malicious ASes or misconfiguration) may falsify the advertised routes (BGP Hijacking)

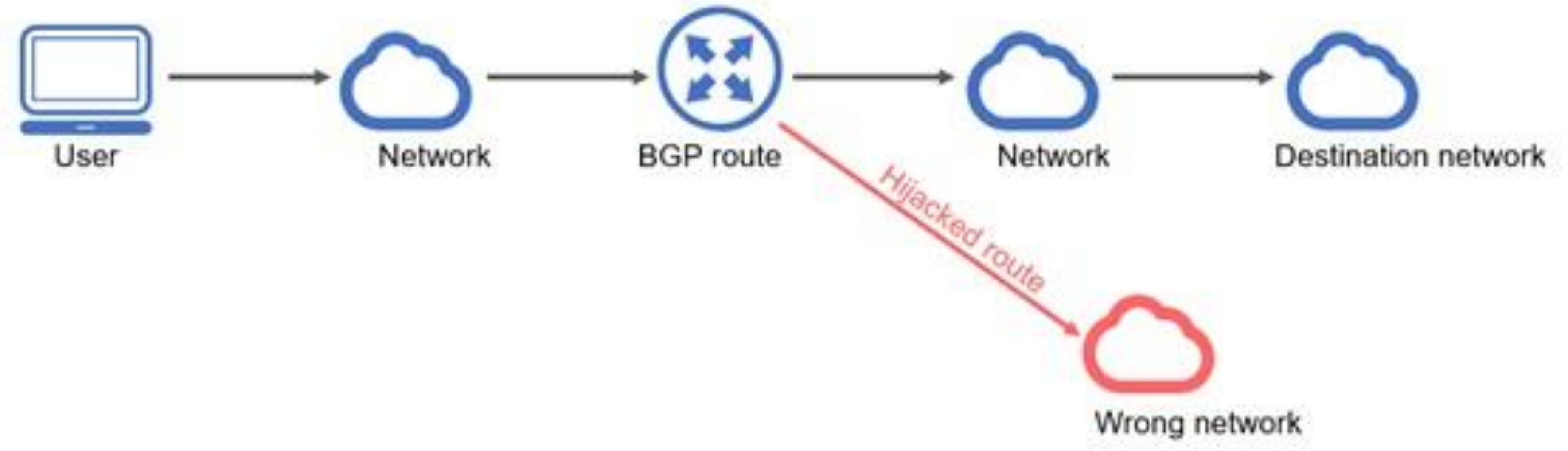

Image: https://nsfocusglobal.com/bgp-hijackings-come-back/

BGP (In)Security

- **BGP update messages contain no authentication or integrity protection**
- **Attacker (malicious ASes or misconfiguration) may falsify the advertised routes (BGP Hijacking)**
    - Modify the IP prefixes associated with a route
        - Can blackhole traffic to certain IP prefixes
    - Change the AS path
        - Either attract traffic to attacker’s AS, or divert traffic away
        - Economic incentive: an ISP wants to dump its traffic on other ISPs without routing their traffic in exchange

BGP (In)Security

- **BGP Hijacking – (Sub-)Prefix Hijacking**
  - Routers perform routing by the manner of the most specific prefix matching (i.e., longest-matching)
    - Adversaries may intentionally announce a prefix “smaller” than originally advertised one
    - A fraction of Internet traffic destined to the prefix to be captured by the adversary
    - Captured traffic is blackholed

BGP (In)Security

- **BGP Hijacking – Path Hijacking (Interception attack)**
  - ASes selectively/incidentally put themselves on the path
    - Adversaries may announce reachability of a prefix to attract traffic to be routed through the AS
    - The interception attack allows the malicious AS to become an intermediate AS in the path
    - Traffic can be routed back – keep the connection alive

BGP (In)Security

- **BGP Incident**
  - Domain advertises good routes to adc
    - Result: packets go into a network ‘
    - April 25, 1997: “The day the Interr
      - AS7007 (Florida Internet Exchang re-advertised all prefixes as if it o
      - In effect, AS7007 was advertising the Internet
      - Huge network instability as incorrect routing data propagated and routers crashed under traffic

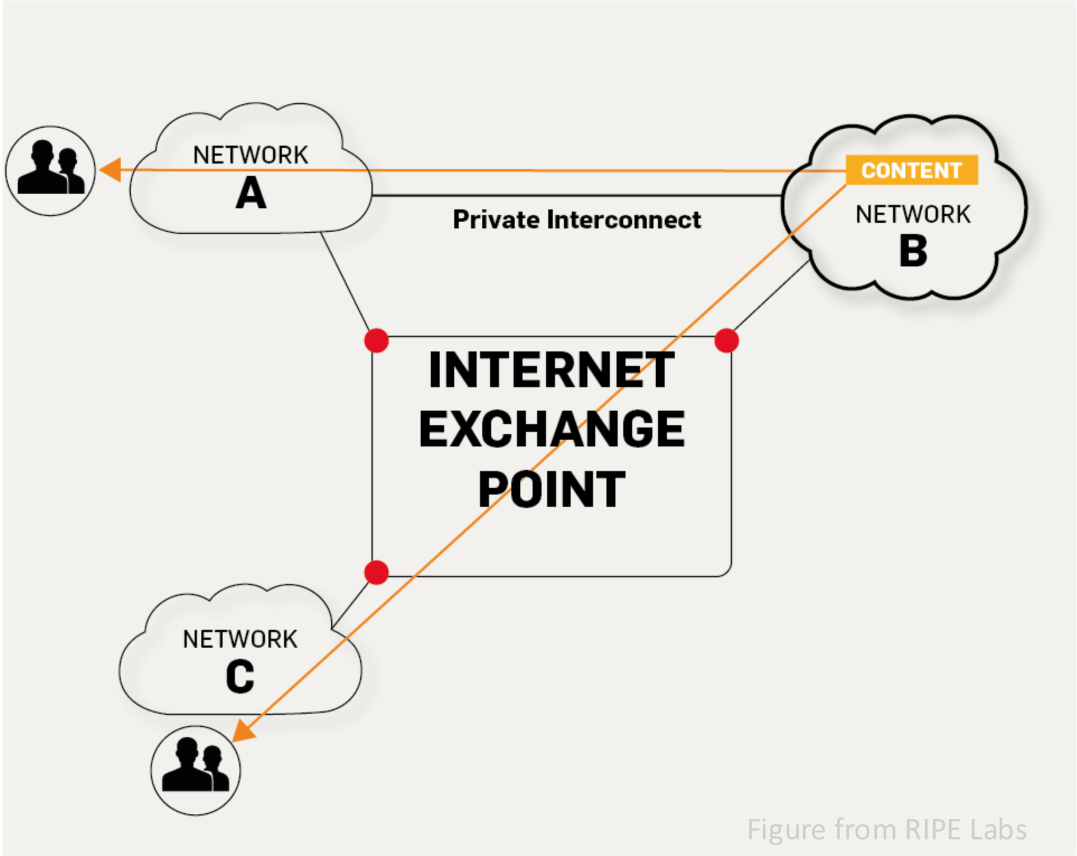

Figure from RIPE Labs

BGP (In)Security

- **BGP Incident**
  - Domain advertises good routes to addresses it does not know how to reach
    - Result: packets go into a network "blackhole"
    - April 25, 1997: "The day the Internet died"
      - AS7007 (Florida Internet Exchange) de-aggregated the BGP route table and re-advertised all prefixes as if it originated paths to them
      - In effect, AS7007 was advertising that it has the best route to every host on the Internet
      - Huge network instability as incorrect routing data propagated and routers crashed under traffic

Figure from RIPE Labs

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      - Huge network instability as incorrect routing data propagated and routers crashed under traffic

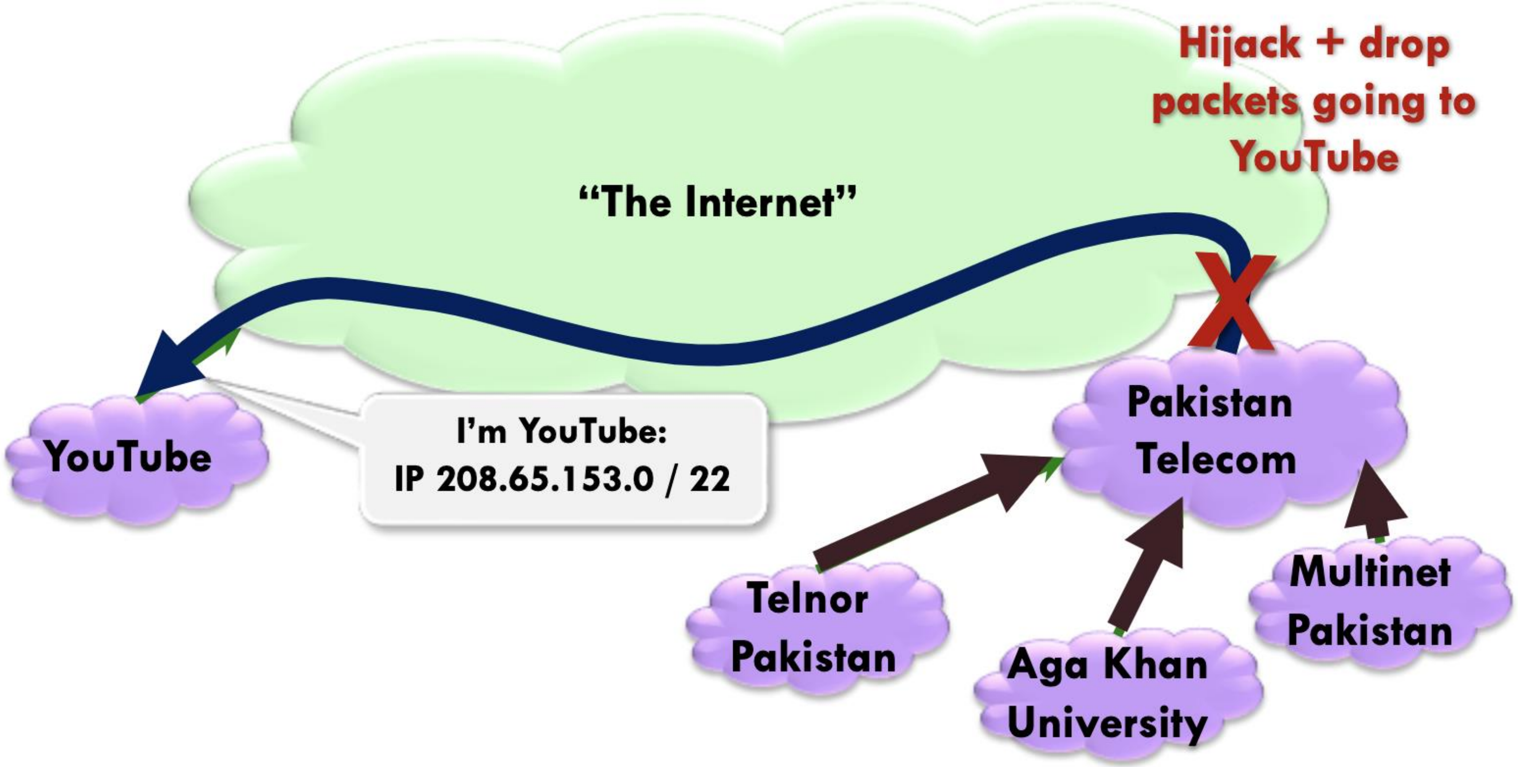
BGP (In)Security

- **BGP Incident:** Pakistan Telecom hijacks YouTube (February 2008)
  - Pakistan government wants to block YouTube
    - AS17557 (Pakistan Telecom) advertises 208.65.153.0/24
    - All YouTube traffic worldwide directed to AS17557

BGP (In)Security

- **BGP Incident:** Pakistan Telecom hijacks YouTube (February 2008)

What should have happened



BGP (In)Security

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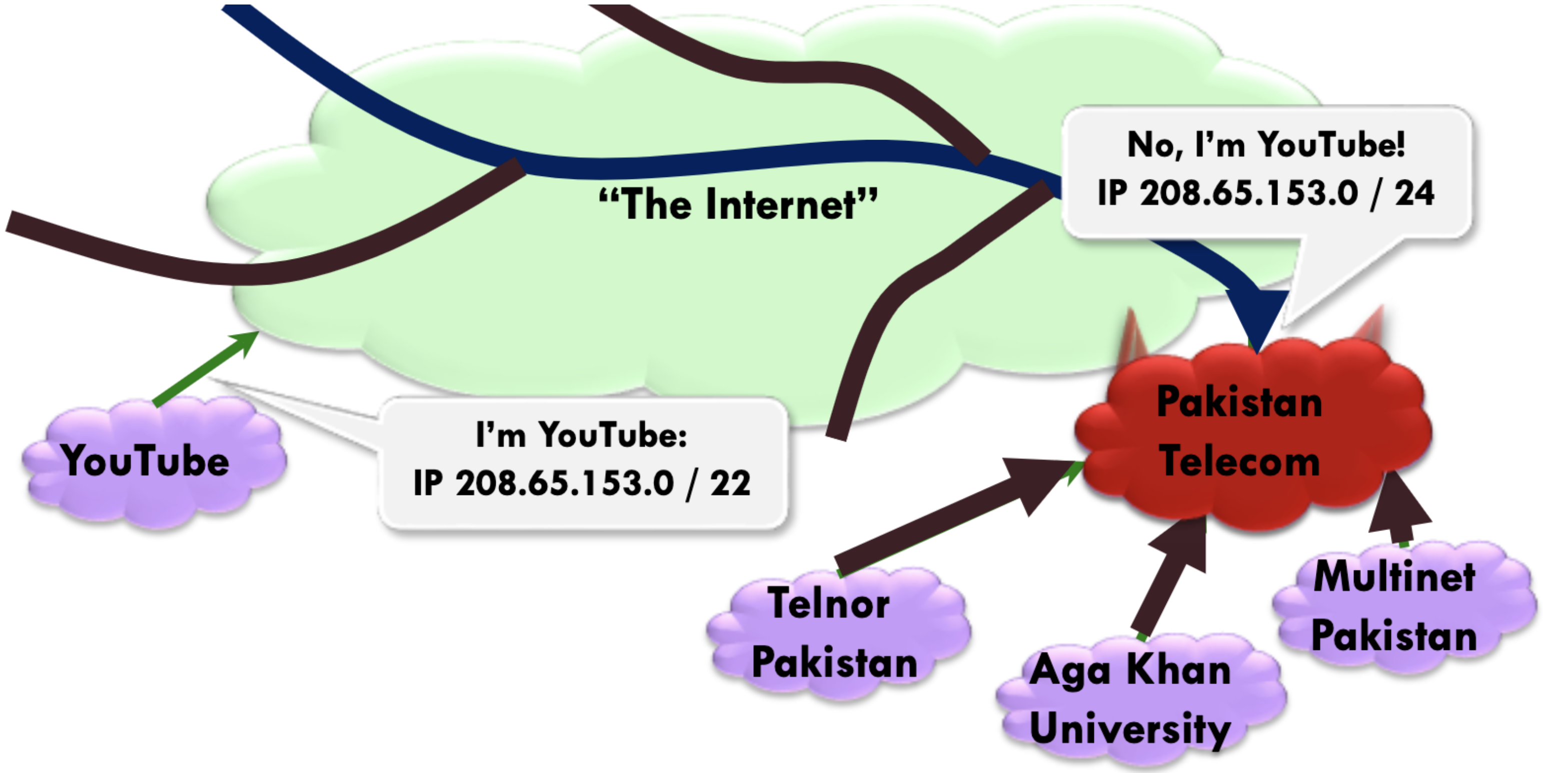
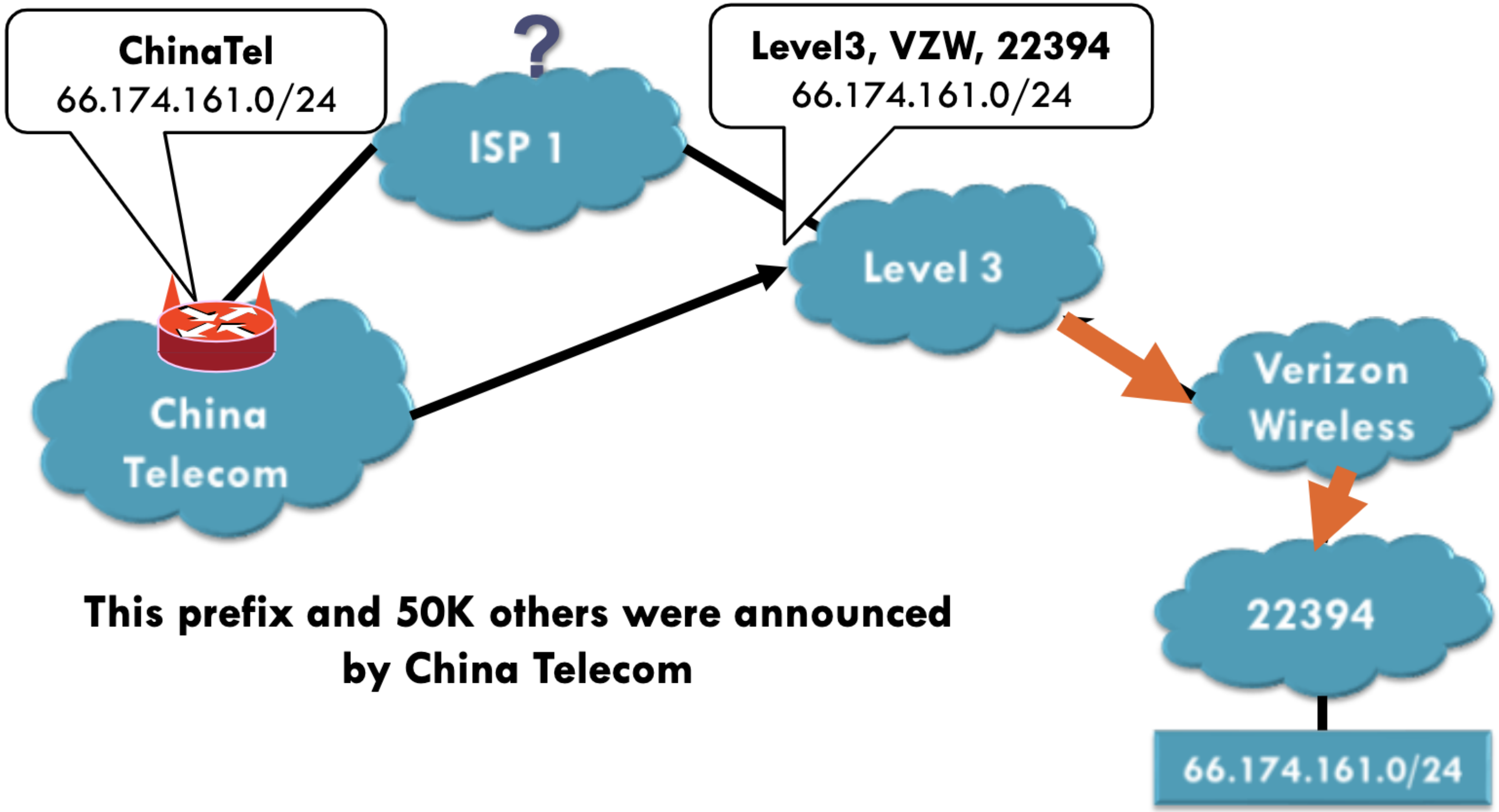
What did happen actually



BGP (In)Security

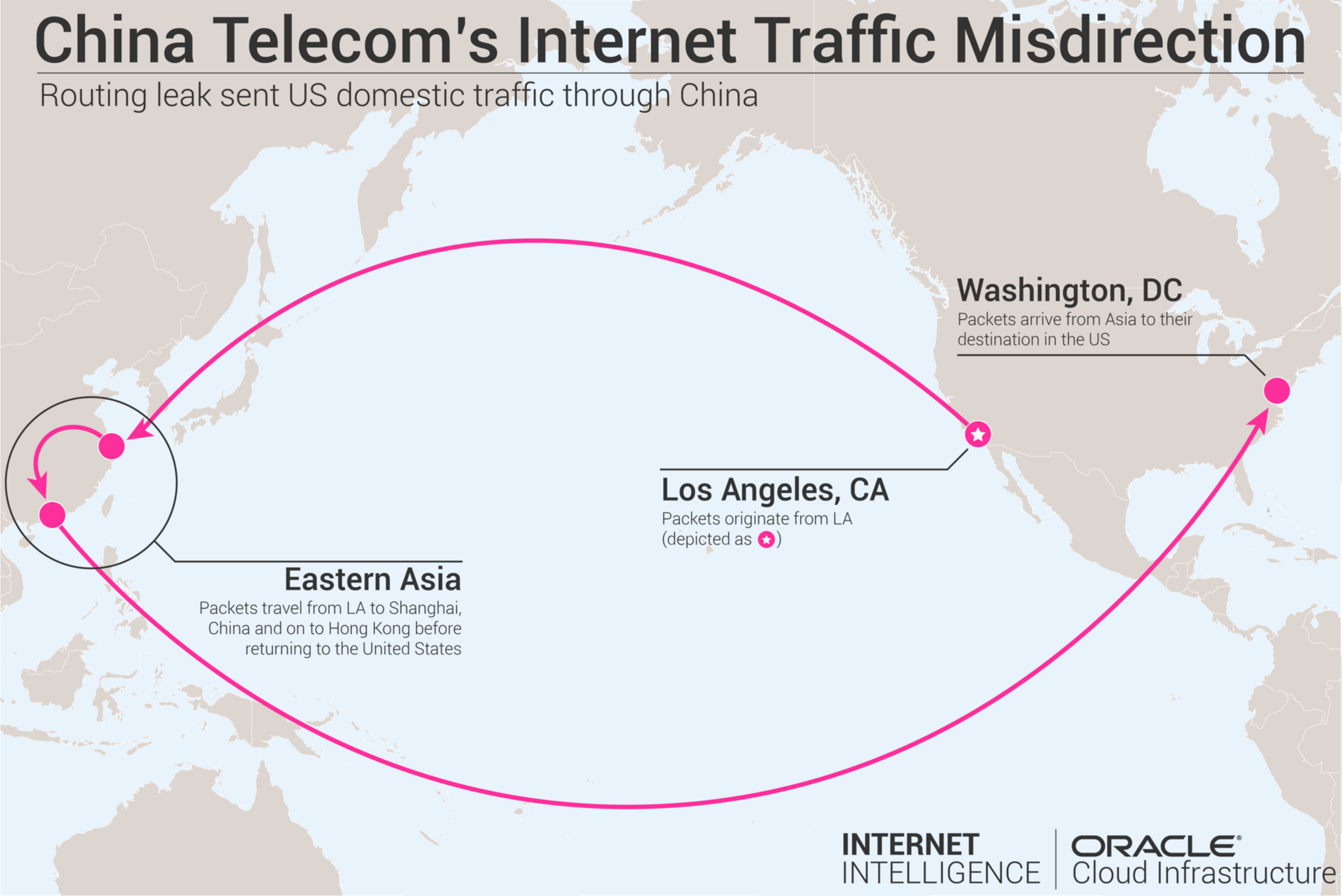
- BGP Incident



This prefix and 50K others were announced by China Telecom

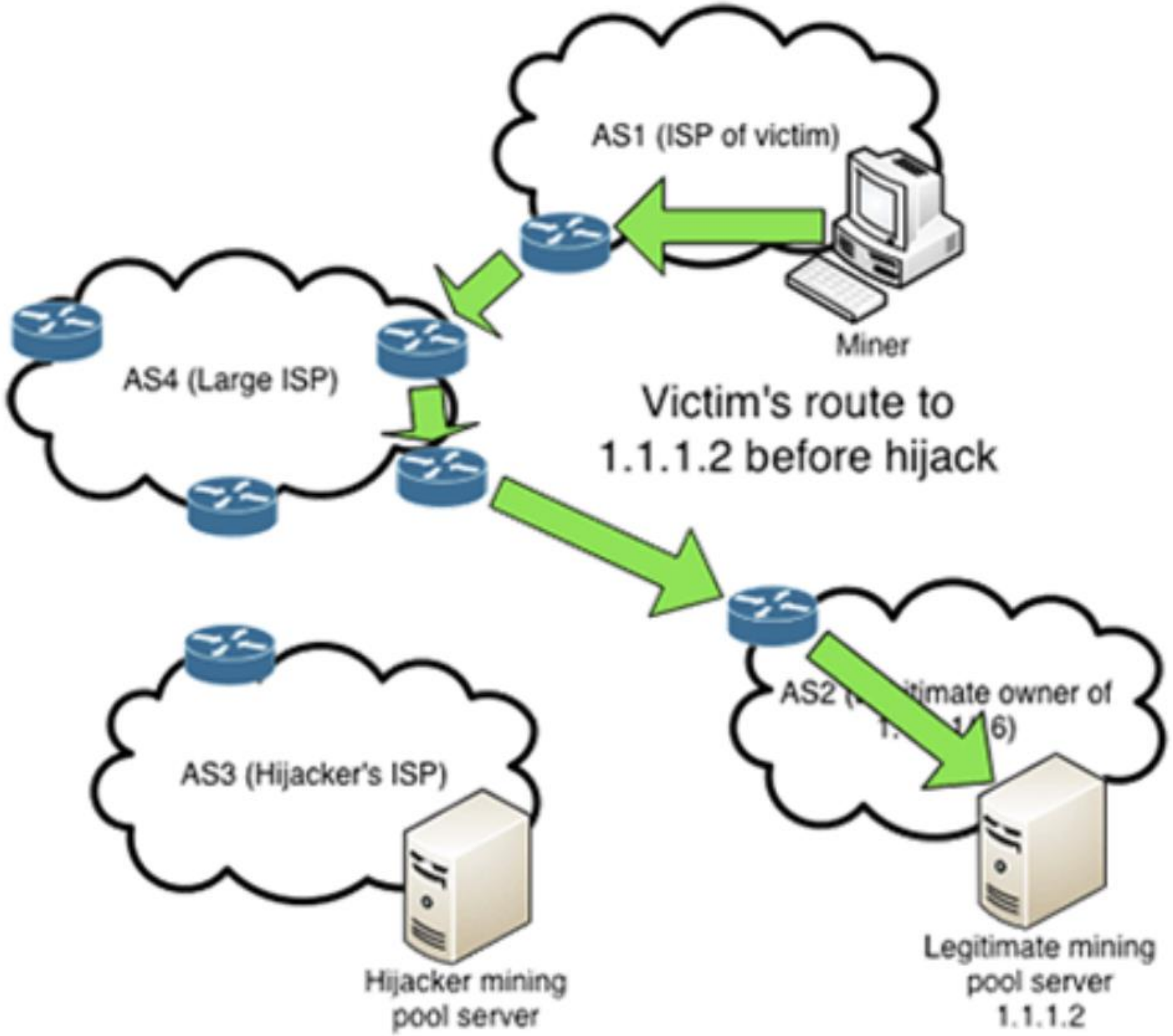
BGP (In)Security

- **BGP Incident**


China Telecom's Internet Traffic Misdirection
Routing leak sent US domestic traffic through China
Washington, DC
Packets arrive from Asia to their destination in the US
Los Angeles, CA
Packets originate from LA (depicted as ✪)
Eastern Asia
Packets travel from LA to Shanghai, China and on to Hong Kong before returning to the United States
INTERNET INTELLIGENCE
ORACLE Cloud Infrastructure

BGP (In)Security

- **BGP Incident**
  - Bitcoin Hijack (February 2014)
    - Hijacked users got directed to a mining server that was under the control of hijacker and redirects them to a malicious mining pool
    - Miners continues to receive mining tasks but don’t get compensated



BGP (In)Security

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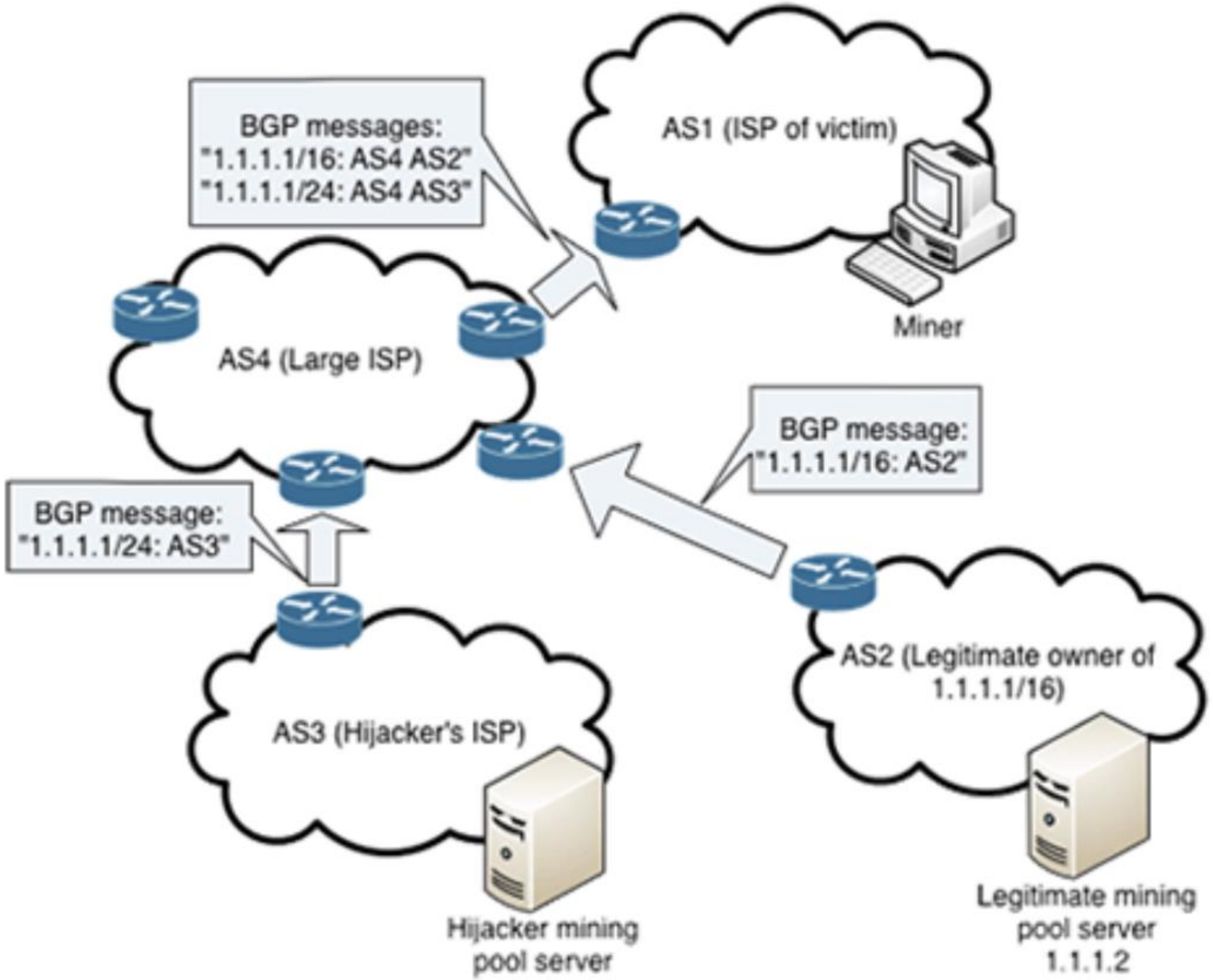

BGP (In)Security

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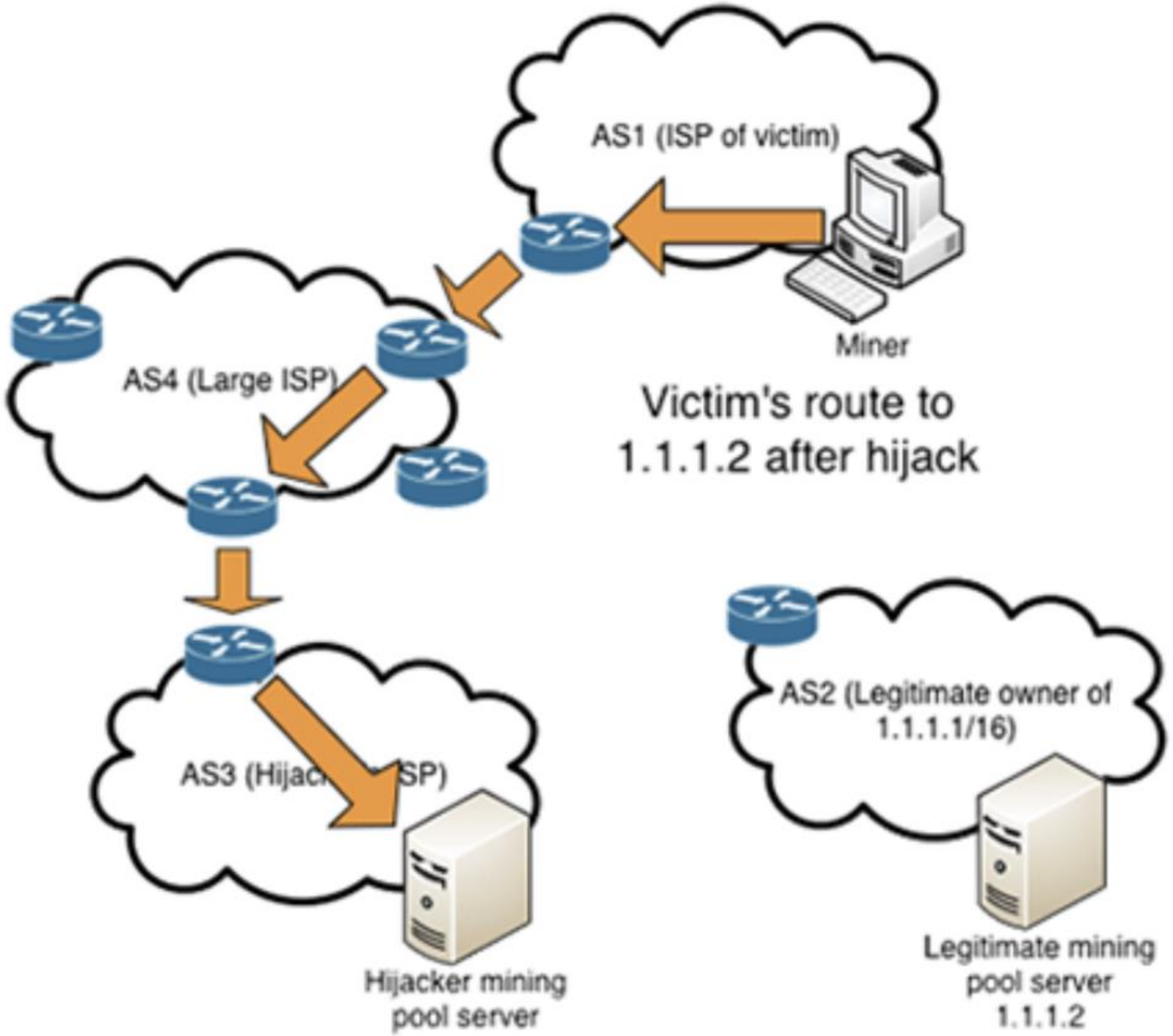

BGP (In)Security

- **Secure BGP is extremely hard**
    - The victim AS doesn't see the problem
        - Picks its own route
    - May not cause entire loss of connectivity
        - Partial damage
        - Performance degradation
    - Diagnosing prefix hijacking
        - Analyzing updates from many vantage points

BGP (In)Security

- **Secure BGP is extremely hard**
    - Complex System
        - Around 100K Autonomous Systems
        - Decentralized Control among ASes
        - Hard to reach agreement on the solution
        - Hard to deploy the solution even standardized
            - Low incentive: many solutions benefit others rather than the deployer itself, e.g., ingress filter to defend IP spoofing

BGP (In)Security

- **Secure BGP is extremely hard**
  - RPKI – Resource Public Key Infrastructure
    - Against prefix hijacking
  - Secure BGP/BGPsec
    - Against path hijacking

Content Delivery Network (CDN)

- **Content Delivery Network**
  - Deploy a large number of edge servers proximal to clients
    - Emerging in late 90s

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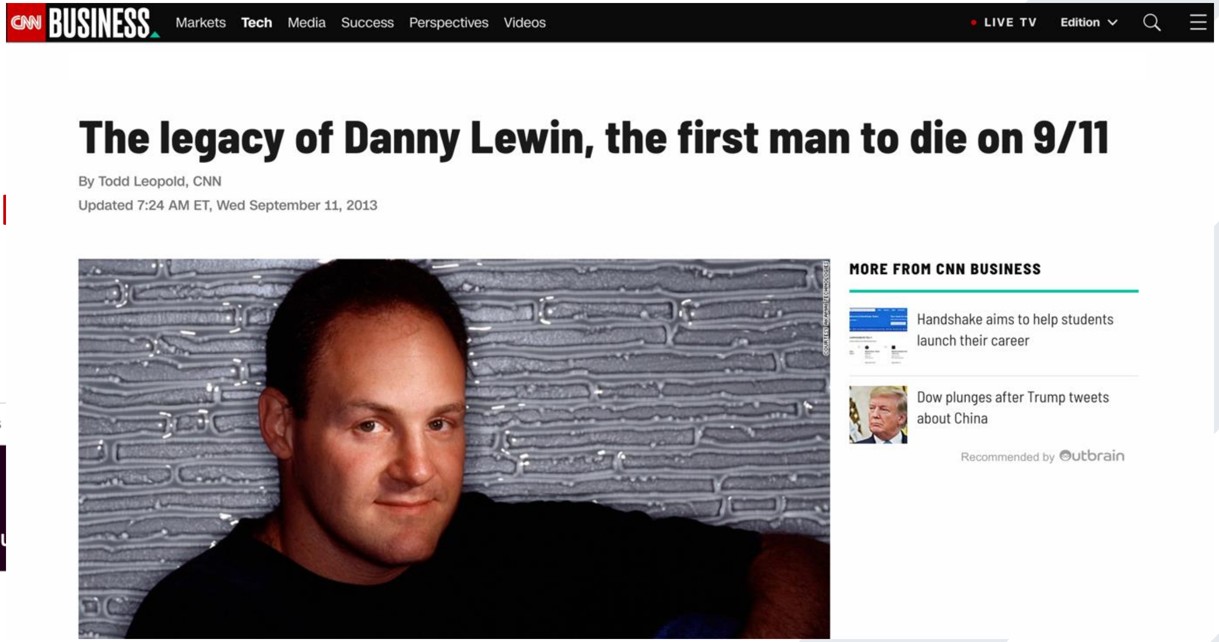

The legacy of Danny Lewin, the first man to die on 9/11

By Todd Leopold, CNN

Updated 7:24 AM ET, Wed September 11, 2013

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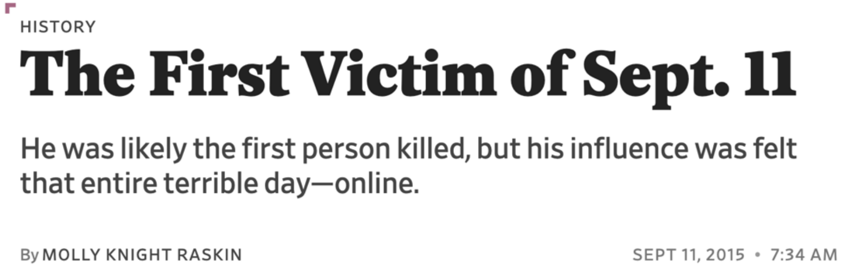


HISTORY

The First Victim of Sept. 11

He was likely the first person killed, but his influence was felt that entire terrible day—online.

By MOLLY KNIGHT RASKIN

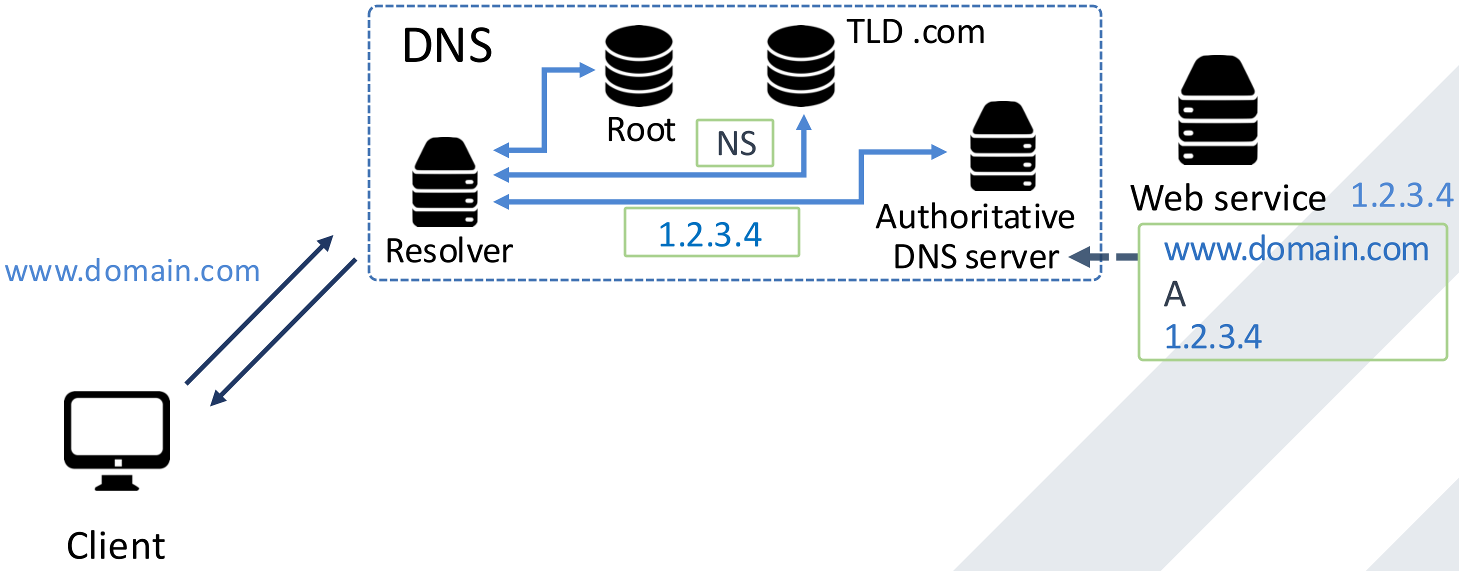
SEPT 11, 2015 • 7:34 AM

Content Delivery Network (CDN)

- **Content Delivery Network**
  - Deploy a large number of edge servers proximal to clients
    - Emerging in late 90s
  - Delivery significant port of Internet traffic
    - All top Internet services leverage CDNs
  - DNS-based CDNs vs. Anycast-based CDNs

Content Delivery Network (CDN)

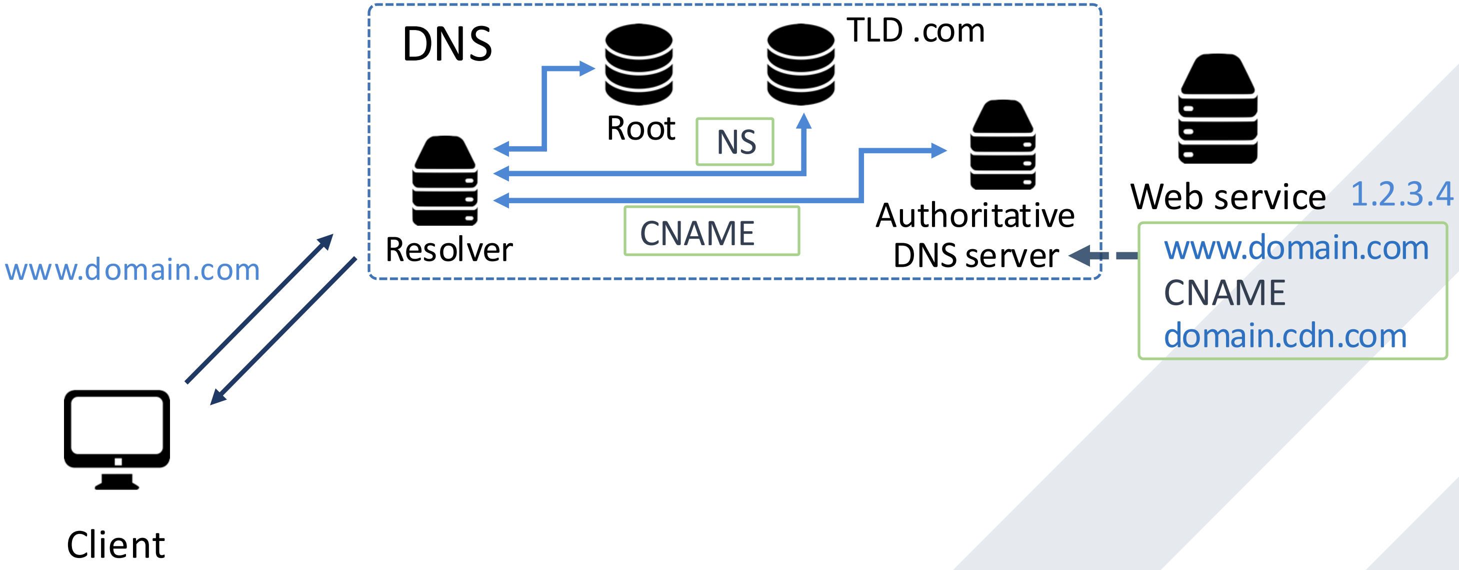
- Content Delivery Network



DNS-based CDNs

Content Delivery Network (CDN)

- **Content Delivery Network**



DNS-based CDNs

Content Delivery Network (CDN)

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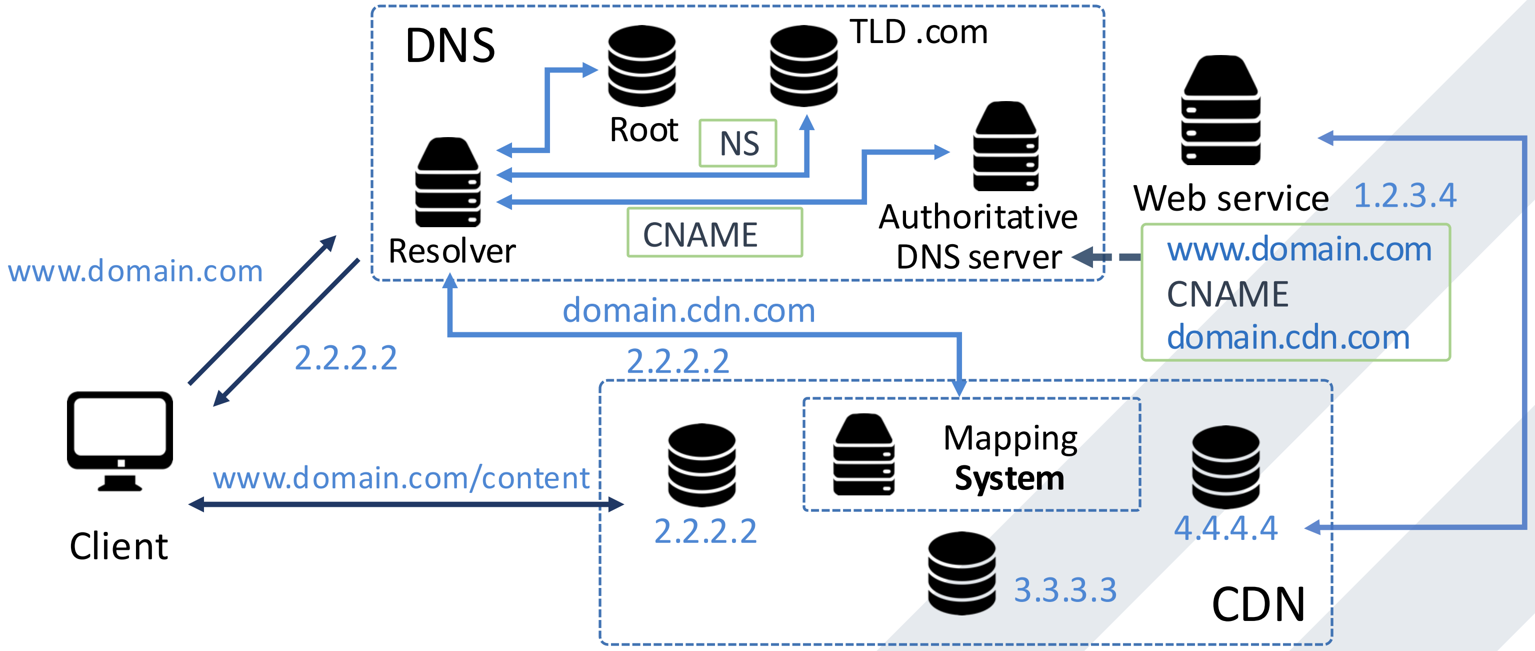
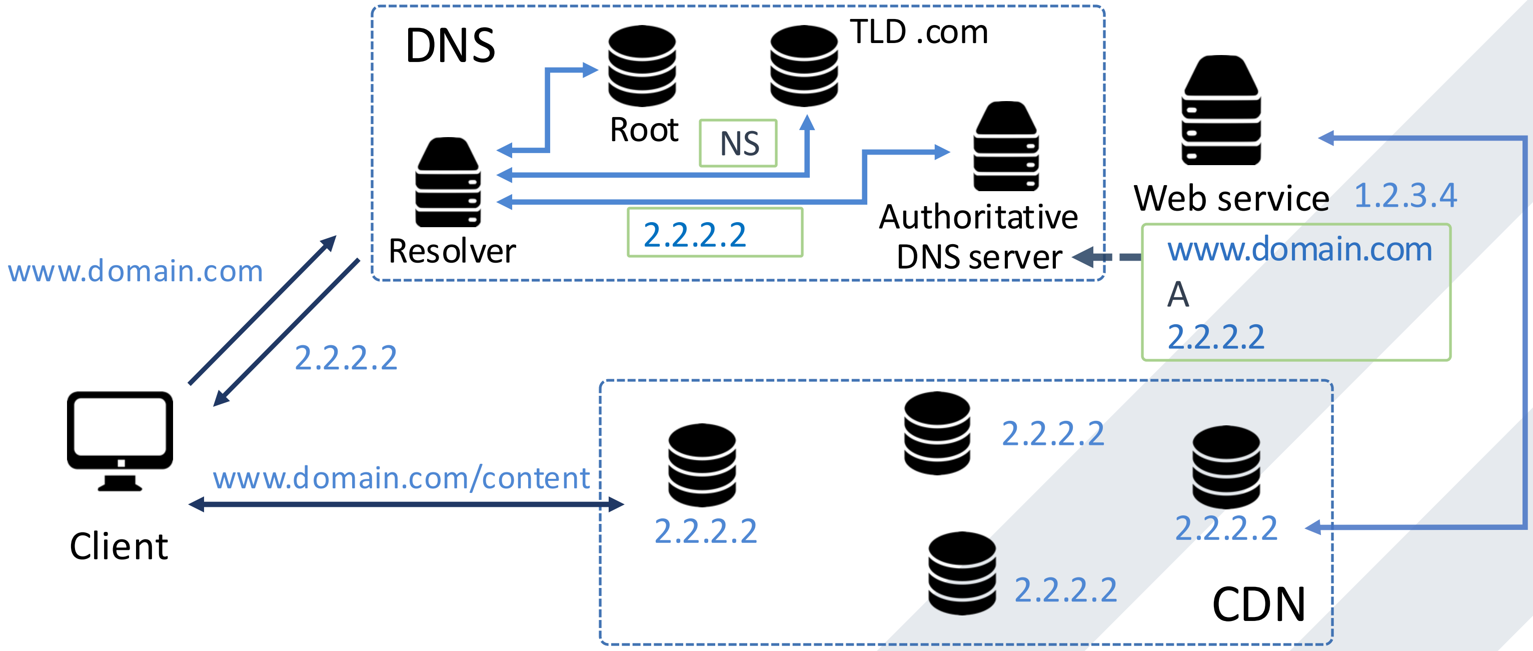


DNS-based CDNs

Content Delivery Network (CDN)

- **Content Delivery Network**



Anycast-based CDNs

Content Delivery Network (CDN)

- **Instinct Security Provided by CDNs**
  - Additional layer of proxy
    - Hide the actual origin source of web services
  - Highly distributed, scalable platforms
    - Absorb malicious traffic (blackholing/scrubbing traffic)
    - Redundancy of service instance
  - Provision of integrity/authentication (TLS/SSL)

Network Security

- TCP/IP
- DNS
- BGP
- (D)DoS Attacks
- CDN

- Applied Cryptography
- PKI

- SSL/TLS and HTTPS
- DNSSEC
- RPKI

CS 772/872: **Advanced Computer and Network Security**

Fall 2025

Course Link:

https://shhaos.github.io/courses/CS872/netsec-fall25.html