

CSCE 463/612

Networks and Distributed Processing
Fall 2025

Application Layer IV

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Chapter 2: Roadmap

2.1 Principles of network applications

2.2 Web and HTTP

2.3 FTP

2.4 Electronic Mail

- SMTP, POP3, IMAP

2.5 DNS (extras)

2.6 P2P file sharing

2.7 Socket programming with TCP

2.8 Socket programming with UDP

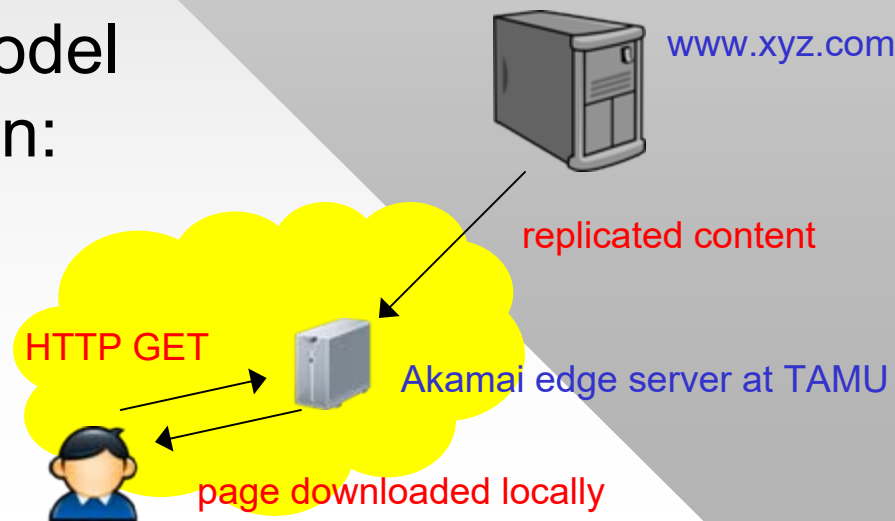
2.9 Building a Web server

DNS Today

- DNS is an old protocol with seemingly simple operation
 - Standardized in 1987, mostly unchanged since then
 - Single-packet query, single-packet response
 - UDP-based operation, no congestion/flow control
 - Timeout-based retransmission
- In practice, DNS is rather complex
 - Many decisions go into writing a good resolver, some of which are still under investigation
 - Topic of ongoing research in security, distributed systems, Internet measurement, future network architecture
- Goal now is to understand the limitations of DNS, its vulnerabilities, and various uses

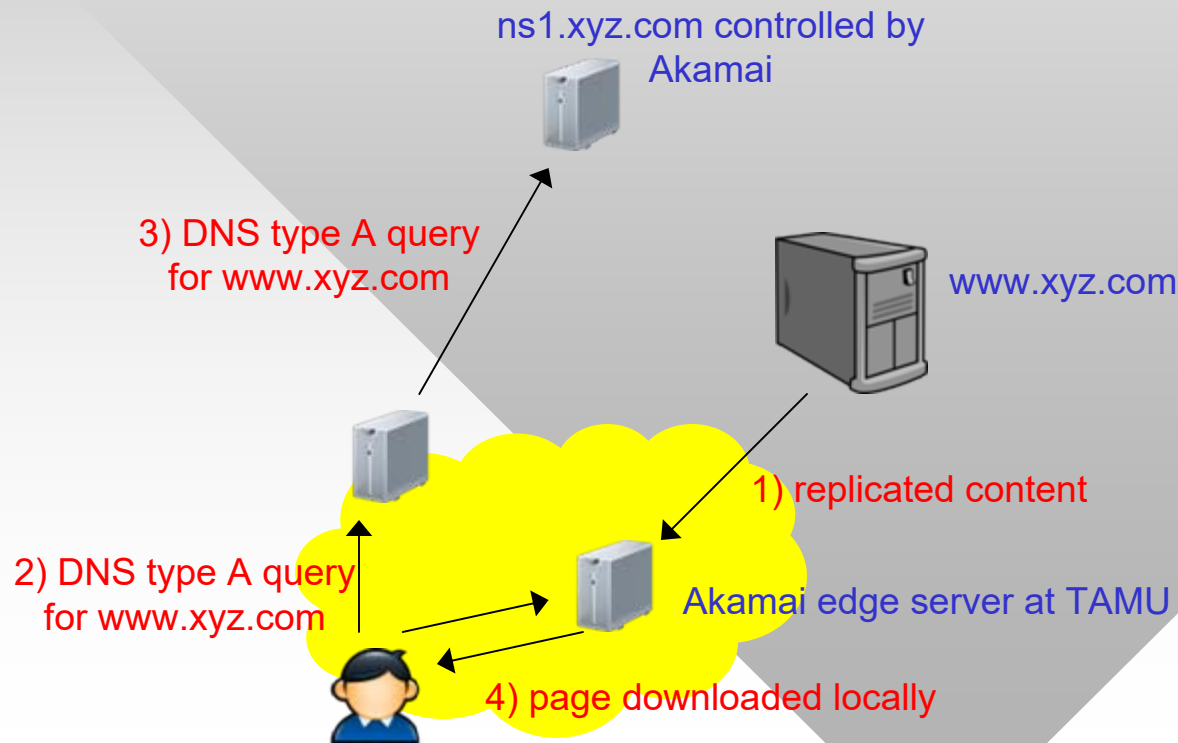
CDNs

- Content Distribution Networks (CDNs)
 - Push replicated content (files, video, images) towards edges
 - Distributed system of application-layer servers
- One of the pioneering CDNs is Akamai
 - J. Dilley, B. Maggs, J. Parikh, H. Prokop, R. Sitaraman, and B. Weihl, “Globally Distributed Content Delivery,” IEEE Internet Computing, Sep/Oct 2002.
- Desired model of operation:



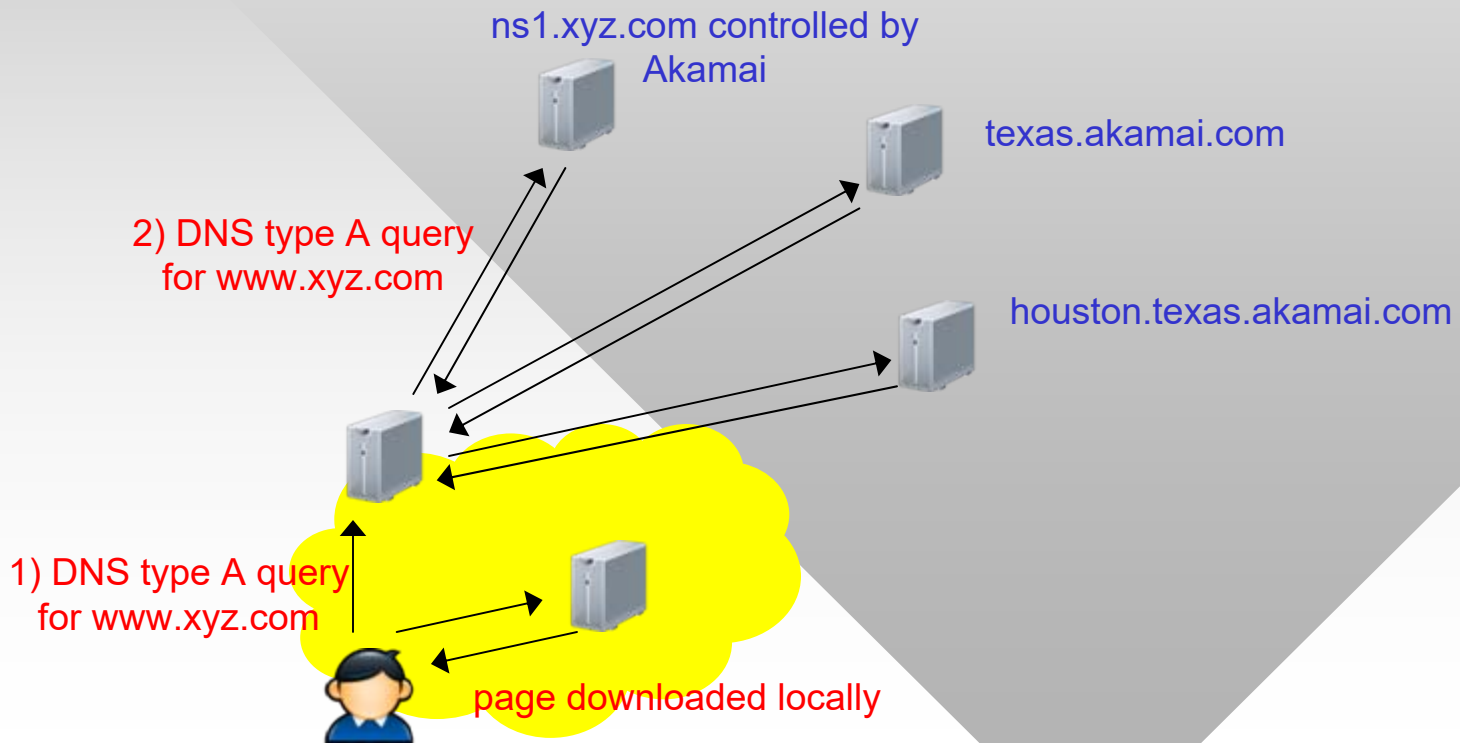
CDNs 2

- How to direct user to closest replica?
 - Akamai relies on DNS to bounce the user to the best server
 - Based on the location of the user's local resolver (e.g., using distance, load, latency, available bandwidth)



CDNs 3

- How many servers are there?
 - Around 365K in 135 countries and 1350 networks
- Often Akamai produces long redirect chains
 - Usually through CNAMEs based on the IP of local resolver



CDNs 4

- One research problem in CDNs is how to determine best edge server for the user
 - If multiple options are present, which one is better?
 - What if closest server is overloaded?
 - Not all servers have every possible version of content
 - Need to account for ISP agreements on bandwidth
- Example:
 - Lookup from Germany gives out an IP in Frankfurt

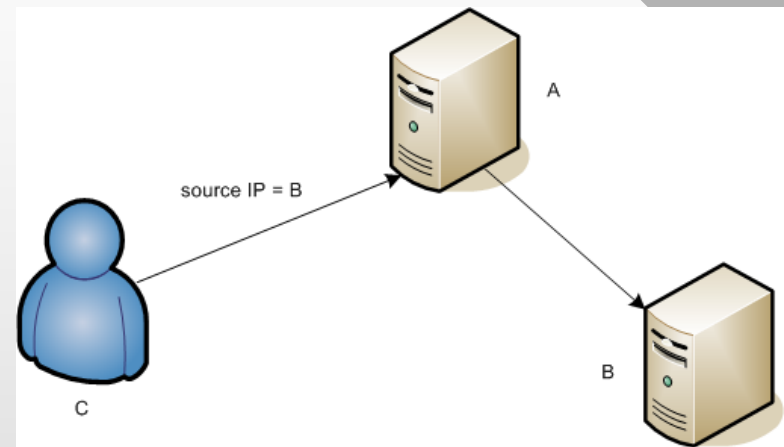
```
www.dhs.gov CNAME www.dhs.gov.edgekey.net
www.dhs.gov.edgekey.net CNAME e4340.dscg.akamaiedge.net
e4340.dscg.akamaiedge.net A 23.45.237.161 (TTL 20 seconds)
```

- Same lookup from TAMU produces an IP in Dallas

CDNs 5

- One pitfall of CDNs is that distance from user to their local resolver is generally unknown
 - May lead to inaccuracies for large ISPs
- Another drawback is long resolution chains
 - 15 CNAMEs back-to-back is not just huge latency, but also prone to incorrect configuration, dead-ends, loops
 - Caching helps with latency, but Akamai uses extremely small TTLs (e.g., 20 sec), so might still be an issue
- Useful online tools
 - dnswatch.info shows a full trace of lookups from the root
 - ip2location.com, ipgeolocation.io map IPs to country/city
 - Registrars (e.g., ARIN, RIPE) allocate subnets; their whois database can be used to map IPs to owner networks

DNS Vulnerabilities



- Terminology: IP spoofing
 - Packets with fake source IP
- For spoofing to work, ISP network of attacker must allow such packets to depart
 - Robert Beverly, Arthur Berger, Young Hyun, and K Claffy, “Understanding the Efficacy of Deployed Internet Source Address Validation Filtering,” ACM IMC, 2009
 - Of 12K IPs tested, 31% were able to spoof (18% across the US, 5% for edu and home networks)
- TCP spoofing is hard
 - Almost impossible to complete the handshake without knowing parameters of the response packet (only B sees them)
- However, UDP spoofing is easy

DNS Vulnerabilities 2

- Terminology: amplification attacks
 - Attacker transmits small packets to intermediate hosts, which then generate **more** traffic towards the victim
 - Relies on spoofing the IP of the victim
 - Difficult to trace as the attacker remains hidden
- **DNS amplification** (1999)
 - Short questions produce large replies, combined with spoofing
 - Large reply = many answers or additional records
- How much amplification can be achieved?
 - IP+UDP+DNS headers = 40 bytes, question $\approx$ 15 bytes
 - Maximum reply is 512 bytes over UDP, ratio 9.3:1
 - 1 Mbps upstream bandwidth per attacker host $\rightarrow$ 9.3 Mbps

DNS Vulnerabilities 3

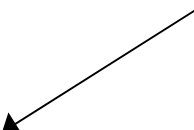
- 1000 hijacked hosts → 9.3 Gbps
 - Even a tiny **botnet** (collection of infected computers under centralized control) can saturate 10 Gbps link
- Main problem: how to find DNS zone with large replies?
- 1) DNS **TXT** queries
 - Some text associated with a host/domain

```
C:\>nslookup -querytype=txt google.com
Server:  s18.irl.cs.tamu.edu
Address: 128.194.135.58
```

Non-authoritative answer:

```
google.com      text = "v=spf1 include:_netblocks.google.com ip4:216.73.93.70/31
ip4:216.73.93.72/31 ~all"
```

Sender Policy Framework (SPF)
shows which IPs are authorized to
send email on behalf of this domain



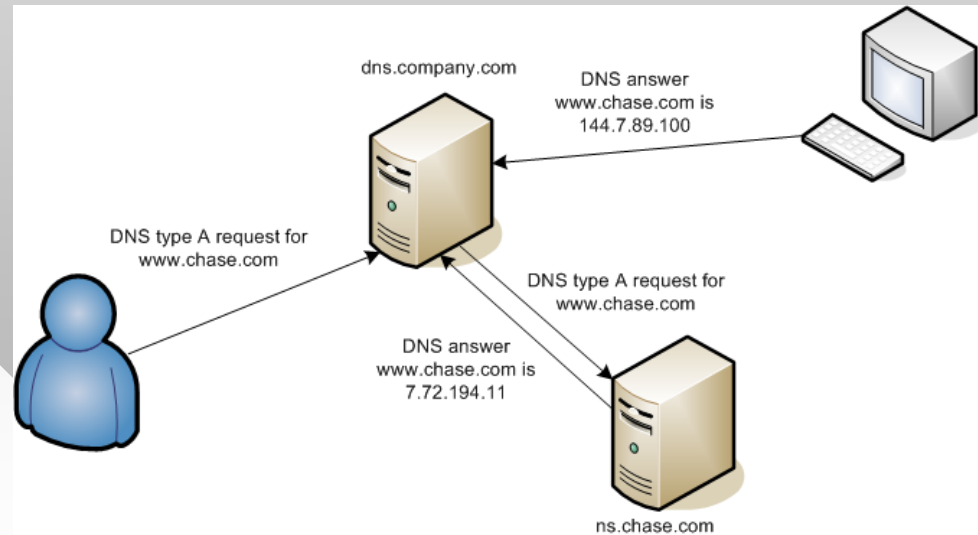
- Text may be large, which leads to easy amplification
 - Traditionally, TXT records were rare; however, new spam-related verification protocols are now actively using them

DNS Vulnerabilities 4

- 2) Domains with many A records/host
 - Google used to return 11 IPs (212 bytes per packet)
- 3) IPv6 queries (type **AAAA**) and SOA
 - IPv6 addresses are 16 bytes, SOA contains lots of fields
- 4) DNS extensions (**EDNS**)
 - Extensions to DNS that support large packets
 - Necessary for signed replies (DNSSEC)
- Amplification falls under the umbrella of **DDoS** (**Distributed Denial of Service**) attacks
 - Goal is to overload target server with incoming traffic
- Terminology: insertion of falsified records into local DNS resolver is called **cache poisoning**

DNS Vulnerabilities 5

- **Remote TXID Guess** attack (1997)
 - DNS responses cannot be verified for authenticity
 - Possible for attacker to send fake replies to fool local resolver
 - With fake DNS replies, user may arrive to a phishing server and allow attackers to steal their login credentials
- 1) Attacker must know
 - Local DNS server's IP
 - Query string
- 2) Attacker must send fake reply **quicker** than the authoritative server
 - DNS servers use only the first reply they get, ignore all others

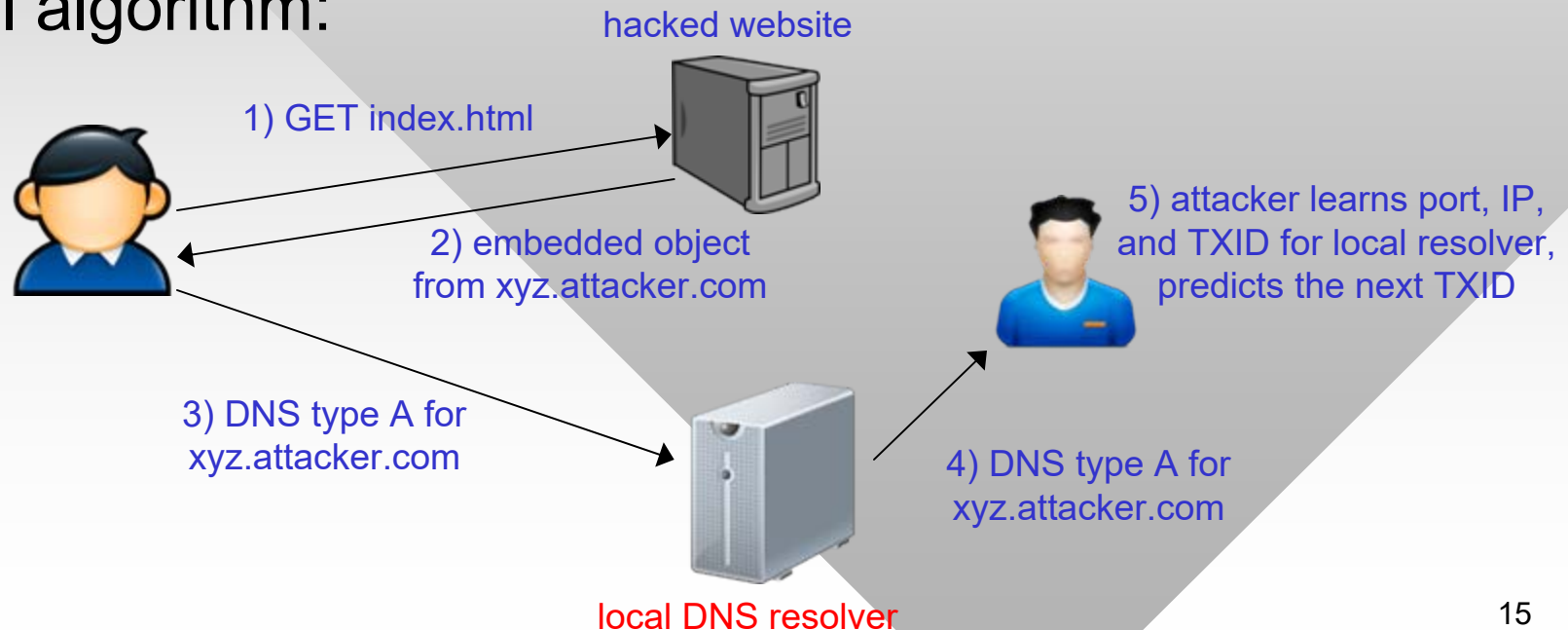


DNS Vulnerabilities 6

- Early DNS implementations included protection mechanisms against this type of attack
- Recursive DNS resolver rejects answers unless:
 - Source IP of reply matches that of the authoritative server
 - Local port number used by recursive resolver is correct
 - TXID in DNS header matches that of the query
- 3) Attacker must spoof source IP of authoritative server
 - Not difficult if the lookup string (www.chase.com) is known
 - If multiple authoritative servers for chase.com, spoof them all
- 4) Attacker must guess local DNS port number
 - Old DNS servers picked a random port during boot and used it for all outgoing queries, which makes things easier

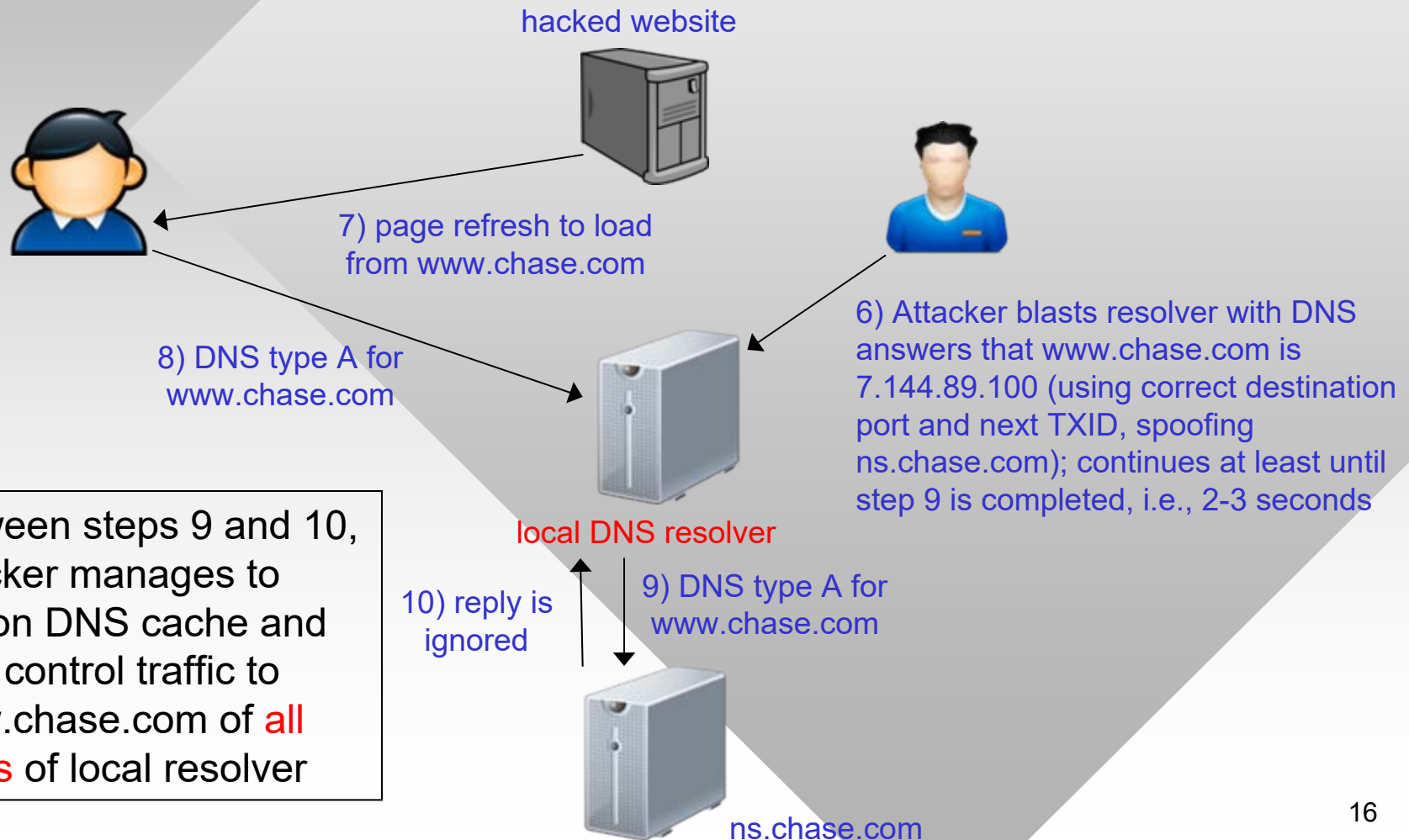
DNS Vulnerabilities 7

- 5) Attacker must guess the TXID of the query
 - Possible only if **local resolver (LR)** uses predictable TXIDs
 - Many older implementations simply incremented the TXID between the queries or used deterministic random number generators with a fixed seed
- Full algorithm:



DNS Vulnerabilities 8

- Full algorithm (cont'd):



Improvements

Birthday problem: in a group of N people, what is the probability that two of them have the same birthday (out of 366 possible birthdays)?

→ Paradox: 100% with 367 people, 99% with 57, and 50% with 23

- Remote TXID Guess attack is difficult
 - Getting user to visit hijacked website is non-trivial
 - Most modern DNS servers now use unpredictable TXIDs
- The next method works around these possibilities
- Suppose LR transmits each query to authoritative server, **even if the same hostname is already pending**
 - Each repeated query gets a **new TXID**
 - BIND 8.2 did this if questions came from unique source IPs
- **Birthday paradox** (2002) relies on rogue local users
 - Attacker forces local resolver to perform lookups for www.chase.com N times back-to-back using N unique IPs
 - After N requests, attacker blasts N answers at LR with random TXIDs, spoofing ns.chase.com's IP address

Improvements 2

- Probability of success $p(N)$ scales **quadratically** in N
 - Define $M = 2^{16}$ to be the size of TXID space
 - First guess is incorrect with probability $1 - N/M$
 - Second with $1 - N/(M-1)$, third $1 - N/(M-2)$, etc.
 - Approximations are accurate for $N \ll M$

$$p(N) = 1 - \prod_{i=0}^{N-1} \left(1 - \frac{N}{M-i}\right) \approx 1 - \left(1 - \frac{N}{M}\right)^N \approx 1 - e^{-N^2/M} \approx \frac{N^2}{M}$$

- Examples
 - $p(1) = 2^{-16}$, $p(10) = 0.15\%$, $p(128) = 22\%$, $p(512) = 98\%$
 - Note that $p(N) = 100\%$ for $N > M / 2$
- What if www.chase.com is already cached by LR?
 - Both Birthday Paradox and Remote TXID Guess fail

Improvements 3

- Attacker must wait until target expires, then pull off attack **just before the host gets cached again**
 - For popular websites, window of opportunity is small
- **Kaminsky exploit** (2008) works around this problem
 - Noticed a loophole: NS records override cached versions if *they come from an authoritative server*
 - LR's outbound port is known, but all other bugs are fixed (i.e., TXID is unpredictable, one pending request per hostname)
- Local user issues request for hash1.chase.com
 - Sends K spoofed packets to LR with random TXIDs
 - Spoofed packets **have no answers**, only NS and additional records for domain chase.com
- **Response manages to overwrite existing NS entries!**

Improvements 4

- Modeling probability of success
 - First packet is a correct guess with probability $1/M$
 - Second packet with probability $1/(M-1)$, third $1/(M-2)$, etc.
- If attack does not work, repeat with hash2.chase.com
 - Each attempt is independent, thus the probability to fail is the product of individual probabilities to fail in each attempt
- After N attempts ($N \cdot K$ packets), we have:

$$p(K, N) = 1 - \prod_{i=0}^{K-1} \left(1 - \frac{1}{M-i}\right)^N \approx 1 - \left(1 - \frac{1}{M}\right)^{KN} \approx 1 - e^{-KN/M}$$

- Kaminsky broke common DNS implementations (IIS, BIND) in about 10 seconds
 - $p(100, 10) = 1.5\%$, $p(250, 40) = 14\%$, $p(500, 200) = 78\%$

Improvements 5

- Why can't K be equal to M?
 - May not have enough bandwidth before ns.chase.com replies
- Closing the Kaminsky loophole
 - Randomization of port numbers for each query (IIS, BIND)
 - Random capitalization of query strings (wWw.ChasE.coM) and **case-sensitive** comparison of answers (Pydig, Unbound)
 - Rejection of new NS records if already cached (not recommended in case domain needs to override old answers)
- With port randomization, $M = 2^{32}$ possibilities
 - Windows 7-10 has 16K (default) available ports, $M = 2^{30} = 1\text{B}$
- Random capitalization adds 2^S options, $S = \text{host len}$
 - For the average Internet hostname, $S = 20$
 - This increases M by an additional factor of 1M