CSci 4271W
Development of Secure Software Systems
Day 19: Network protocols, cont'd

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Outline

Public key authenticity

- Public keys don't need to be secret, but they must be right
- Wrong key $\rightarrow$ can't stop middleperson
- So we still have a pretty hard distribution problem

Symmetric key servers

- Users share keys with server, server distributes session keys
- Symmetric key-exchange protocols, or channels
- Standard: Kerberos
- Drawback: central point of trust

Certificates

- A name and a public key, signed by someone else
  - $C_A = \text{Sign}_S(A, K_A)$
- Basic unit of transitive trust
- Commonly use a complex standard "X.509"

Certificate authorities

- "CA" for short: entities who sign certificates
- Simplest model: one central CA
- Works for a single organization, not the whole world

Web of trust

- Pioneered in PGP for email encryption
- Everyone is potentially a CA: trust people you know
- Works best with security-motivated users
  - Ever attended a key signing party?

CA hierarchies

- Organize CAs in a tree
- Distributed, but centralized (like DNS)
- Check by follow a path to the root
- Best practice: sub CAs are limited in what they certify

PKI for authorization

- Enterprise PKI can link up with permissions
- One approach: PKI maps key to name, ACL maps name to permissions
- Often better: link key with permissions directly, name is a comment
  - More like capabilities

The revocation problem

- How can we make certs "go away" when needed?
- Impossible without being online somehow

1. Short expiration times
2. Certificate revocation lists
3. Certificate status checking

Outline

Key distribution and PKI

Cryptographic protocols, cont'd

Blind SQL injection (demo)

SSH

SSL/TLS

More causes of crypto failure

Abstract protocols

- Outline of what information is communicated in messages
  - Omit most details of encoding, naming, sizes, choice of ciphers, etc.
- Describes honest operation
  - But must be secure against adversarial participants
- Seemingly simple, but many subtle problems

Protocol notation

$A \to B : N_B, \{T_0, B, N_B\}_{K_B}$

- $A \to B$: message sent from Alice intended for Bob
- B (after :): Bob's name
- $\{\cdots\}_K$: encryption with key K

Anti-pattern: "oracle"

- Any way a legitimate protocol service can give a capability to an adversary
- Can exist whenever a party decrypts, signs, etc.
- "Padding oracle" was an instance of this at the implementation level

Needham-Schroeder

Mutual authentication via nonce exchange, assuming public keys (core):

$A \to B: \{N_A, A\}_{E_B}$

$B \to A: \{N_A, N_B\}_{E_A}$

$A \to B: \{N_B\}_{E_B}$

Needham-Schroeder MITM

$A \to C: \{N_A, A\}_{E_C}$

$C \to B: \{N_A, A\}_{E_B}$

$B \to C: \{N_A, N_B\}_{E_A}$

$C \to A: \{N_A, N_B\}_{E_A}$

$A \to C: \{N_B\}_{E_C}$

$C \to B: \{N_B\}_{E_B}$

Certificates, Denning-Sacco

- A certificate signed by a trusted third-party S binds an identity to a public key
  - $C_A = \text{Sign}_S(A, K_A)$
- Suppose we want to use S in establishing a session key K_{AB}:

$$\begin{aligned} A \to S:&\ A, B \\ S \to A:&\ C_A, C_B \\ A \to B:&\ C_A, C_B, \{\text{Sign}_A(K_{AB})\}_{K_B} \end{aligned}$$

Attack against Denning-Sacco

$$\begin{aligned} A \to S:&\ A, B \\ S \to A:&\ C_A, C_B \\ A \to B:&\ C_A, C_B, \{\text{Sign}_A(K_{AB})\}_{K_B} \\ \hline B \to S:&\ B, C \\ S \to B:&\ C_B, C_C \\ B \to C:&\ C_A, C_C, \{\text{Sign}_A(K_{AB})\}_{K_C} \end{aligned}$$

By re-encrypting the signed key, Bob can pretend to be Alice to Charlie

Envelopes analogy

- Encrypt then sign, or vice-versa?
- On paper, we usually sign inside an envelope, not outside. Two reasons:
  - Attacker gets letter, puts in his own envelope (c.f. attack against X.509)
  - Signer claims "didn't know what was in the envelope" (failure of non-repudiation)

Design robustness principles

- Use timestamps or nonces for freshness
- Be explicit about the context
- Don't trust the secrecy of others' secrets
- Whenever you sign or decrypt, beware of being an oracle
- Distinguish runs of a protocol

Implementation principles

- Ensure unique message types and parsing
- Design for ciphers and key sizes to change
- Limit information in outbound error messages
- Be careful with out-of-order messages

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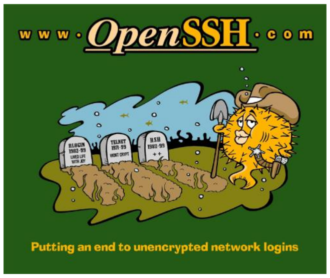
Short history of SSH

- Started out as freeware by Tatu Ylönen in 1995
- Original version commercialized
- Fully open-source OpenSSH from OpenBSD
- Protocol redesigned and standardized for "SSH 2"

OpenSSH t-shirt



SSH host keys

- Every SSH server has a public/private keypair
- Ideally, never changes once SSH is installed
- Early generation a classic entropy problem
  - Especially embedded systems, VMs

Authentication methods

- Password, encrypted over channel
- `.shosts`: like `.rhosts`, but using client host key
- User-specific keypair
  - Public half on server, private on client
- Plugins for Kerberos, PAM modules, etc.

Old crypto vulnerabilities

- 1.x had only CRC for integrity
  - Worst case: when used with RC4
- Injection attacks still possible with CBC
  - CRC compensation attack
- For least-insecure 1.x-compatibility, attack detector
- Alas, detector had integer overflow worse than original attack

Newer crypto vulnerabilities

- IV chaining: IV based on last message ciphertext
  - Allows chosen plaintext attacks
  - Better proposal: separate, random IVs
- Some tricky attacks still left
  - Send byte-by-byte, watch for errors
  - Of arguable exploitability due to abort
- Now migrating to CTR mode

SSH over SSH

- SSH to machine 1, from there to machine 2
  - Common in these days of NATs
- Better: have machine 1 forward an encrypted connection

1. No need to trust 1 for secrecy
2. Timing attacks against password typing

SSH (non-)PKI

- When you connect to a host freshly, a mild note
- When the host key has changed, a large warning

```
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@    WARNING: REMOTE HOST IDENTIFICATION HAS CHANGED!     @
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
IT IS POSSIBLE THAT SOMEONE IS DOING SOMETHING NASTY!
Someone could be eavesdropping on you right now
(man-in-the-middle attack)!
It is also possible that a host key has just been changed.
```

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SSL/TLS

- Developed at Netscape in early days of the public web
  - Usable with other protocols too, e.g. IMAP
- SSL 1.0 pre-public, 2.0 lasted only one year, 3.0 much better
- Renamed to TLS with RFC process
  - TLS 1.0 improves SSL 3.0
- TLS 1.1 and 1.2 in 2006 and 2008, only gradual adoption

IV chaining vulnerability

- TLS 1.0 uses previous ciphertext for CBC IV
- But, easier to attack in TLS:
  - More opportunities to control plaintext
  - Can automatically repeat connection
- "BEAST" automated attack in 2011: TLS 1.1 wakeup call

Compression oracle vuln.

- Compr$(S \parallel A)$, where S should be secret and A is attacker-controlled
- Attacker observes ciphertext length
- If A is similar to S, combination compresses better
- Compression exists separately in HTTP and TLS

But wait, there's more!

- Too many vulnerabilities to mention them all in lecture
- Kaloper-Meršinjak et al. have longer list
  - "Lessons learned" are variable, though
- Meta-message: don't try this at home

HTTPS hierarchical PKI

- Browser has order of 100 root certs
  - Not same set in every browser
  - Standards for selection not always clear
- Many of these in turn have sub-CAs
- Also, "wildcard" certs for individual domains

Hierarchical trust?

- No. Any CA can sign a cert for any domain
- A couple of CA compromises recently
- Most major governments, and many companies you've never heard of, could probably make a `google.com` cert
- Still working on: make browser more picky, compare notes

CA vs. leaf checking bug

- Certs have a bit that says if they're a CA
- All but last entry in chain should have it set
- Browser authors repeatedly fail to check this bit
- Allows any cert to sign any other cert

MD5 certificate collisions

- MD5 collisions allow forging CA certs
- Create innocuous cert and CA cert with same hash
  - Requires some guessing what CA will do, like sequential serial numbers
  - Also 200 PS3s
- Oh, should we stop using that hash function?

CA validation standards

- CA's job to check if the buyer really is `foo.com`
- Race to the bottom problem:
  - CA has minimal liability for bad certs
  - Many people want cheap certs
  - Cost of validation cuts out of profit
- "Extended validation" (green bar) certs attempt to fix

HTTPS and usability

- Many HTTPS security challenges tied with user decisions
- Is this really my bank?
- Seems to be a quite tricky problem
  - Security warnings often ignored, etc.
  - We'll return to this as a major example later

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Random numbers and entropy

- Cryptographic RNGs use cipher-like techniques to provide indistinguishability
- But rely on truly random seeding to stop brute force
  - Extreme case: no entropy $\rightarrow$ always same "randomness"
- Modern best practice: seed pool with 256 bits of entropy
  - Suitable for security levels up to 2^{256}

Netscape RNG failure

- Early versions of Netscape SSL (1994-1995) seeded with:
  - Time of day
  - Process ID
  - Parent process ID
- Best case entropy only 64 bits
  - (Not out of step with using 40-bit encryption)
- But worse because many bits guessable

Debian/OpenSSL RNG failure (1)

- OpenSSL has pretty good scheme using `/dev/urandom`
- Also mixed in some uninitialized variable values
  - "Extra variation can't hurt"
- From modern perspective, this was the original sin
  - Remember undefined behavior discussion?
- But had no immediate ill effects

Debian/OpenSSL RNG failure (2)

- Debian maintainer commented out some lines to fix a Valgrind warning
  - "Potential use of uninitialized value"
- Accidentally disabled most entropy (all but 16 bits)
- Brief mailing list discussion didn't lead to understanding
- Broken library used for ~2 years before discovery

Detected RSA/DSA collisions

- 2012: around 1% of the SSL keys on the public net are breakable
  - Some sites share complete keypairs
  - RSA keys with one prime in common (detected by large-scale GCD)
- One likely culprit: insufficient entropy in key generation
  - Embedded devices, Linux `/dev/urandom` vs. `/dev/random`
- DSA signature algorithm also very vulnerable

New factoring problem (CCS'17)

- An Infineon RSA library used primes of the form $p = k \cdot M + (65537^a \bmod M)$
- Smaller problems: fingerprintable, less entropy
- Major problem: can factor with a variant of Coppersmith's algoritm
  - E.g., 3 CPU months for a 1024-bit key

Side-channel attacks

- Timing analysis:
  - Number of 1 bits in modular exponentiation
  - Unpadding, MAC checking, error handling
  - Probe cache state of AES table entries
- Power analysis
  - Especially useful against smartcards
- Fault injection
- Data non-erasure
  - Hard disks, "cold boot" on RAM

WEP "privacy"

- First WiFi encryption standard: Wired Equivalent Privacy (WEP)
- F&S: designed by a committee that contained no cryptographers
- Problem 1: note "privacy": what about integrity?
  - Nope: stream cipher + CRC = easy bit flipping

WEP shared key

- Single key known by all parties on network
- Easy to compromise
- Hard to change
- Also often disabled by default
- Example: a previous employer

WEP key size and IV size

- Original sizes: 40-bit shared key (export restrictions) plus 24-bit IV = 64-bit RC4 key
  - Both too small
- 128-bit upgrade kept 24-bit IV
  - Vague about how to choose IVs
  - Least bad: sequential, collision takes hours
  - Worse: random or everyone starts at zero

WEP RC4 related key attacks

- Only true crypto weakness
- RC4 "key schedule" vulnerable when:
  - RC4 keys very similar (e.g., same key, similar IV)
  - First stream bytes used
- Not such a problem for other RC4 users like SSL
  - Key from a hash, skip first output bytes

New problem with WPA (CCS'17)

- Session key set up in a 4-message handshake
- Key reinstallation attack: replay #3
  - Causes most implementations to reset nonce and replay counter
  - In turn allowing many other attacks
  - One especially bad case: reset key to 0
- Protocol state machine behavior poorly described in spec
  - Outside the scope of previous security proofs

Trustworthiness of primitives

- Classic worry: DES S-boxes
- Obviously in trouble if cipher chosen by your adversary
- In a public spec, most worrying are unexplained elements
- Best practice: choose constants from well-known math, like digits of π

Dual_EC_DRBG (1)

- Pseudorandom generator in NIST standard, based on elliptic curve
- Looks like provable (slow enough!) but strangely no proof
- Specification includes long unexplained constants
- Academic researchers find:
  - Some EC parts look good
  - But outputs are statistically distinguishable

Dual_EC_DRBG (2)

- Found 2007: special choice of constants allows prediction attacks
  - Big red flag for paranoid academics
- Significant adoption in products sold to US govt. FIPS-140 standards
  - Semi-plausible rationale from RSA (EMC)
- NSA scenario basically confirmed by Snowden leaks
  - NIST and RSA immediately recommend withdrawal