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

\[ A \rightarrow B : N_B, \{T_B, B, N_B\}_{K_B} \]

- \( A \rightarrow B \): message sent from Alice intended for Bob
- \( B \) (after \( : \)): Bob's name
- \( f \) : encryption with key \( K \)

Needham-Schroeder

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

\[
\begin{align*}
A \rightarrow B : & \quad \{N_A, A\}_{E_B} \\
B \rightarrow A : & \quad \{N_A, N_B\}_{E_A} \\
A \rightarrow B : & \quad \{N_B\}_{E_B}
\end{align*}
\]

Needham-Schroeder MITM

\[
\begin{align*}
A \rightarrow C : & \quad \{N_A, A\}_{E_C} \\
C \rightarrow B : & \quad \{N_A, A\}_{E_B} \\
B \rightarrow C : & \quad \{N_A, N_B\}_{E_A} \\
C \rightarrow A : & \quad \{N_A, N_B\}_{E_A} \\
A \rightarrow C : & \quad \{N_B\}_{E_C} \\
C \rightarrow B : & \quad \{N_B\}_{E_B}
\end{align*}
\]

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
  - \( A \rightarrow S : \quad A, B \)
  - key \( K_{AB} \):
    - \( S \rightarrow A : \quad C_A, C_B \)
    - \( A \rightarrow B : \quad C_A, C_B, \{\text{Sign}_A(K_{AB})\}_{K_B} \)

Attack against Denning-Sacco

\[
\begin{align*}
A \rightarrow S : & \quad A, B \\
S \rightarrow A : & \quad C_A, C_B \\
A \rightarrow B : & \quad C_A, C_B, \{\text{Sign}_A(K_{AB})\}_{K_B} \\
B \rightarrow S : & \quad B, C \\
S \rightarrow B : & \quad C_B, C_C \\
B \rightarrow C : & \quad C_A, C_C, \{\text{Sign}_A(K_{AB})\}_{K_C}
\end{align*}
\]

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

Outline

- More crypto protocols
- Announcements intermission
- More causes of crypto failure

Note to early readers

- This is the section of the slides most likely to change in the final version
- If class has already happened, make sure you have the latest slides for announcements

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 → 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 $p = k \cdot M + (65537 \cdot a \mod M)$
- Smaller problems: fingerprintable, less entropy
- Major problem: can factor with a variant of Coppersmith's algorithm
  - 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 a practical 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