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Issues in the Design of Authentication and Key Exchange Protocols

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Basic Protocols

- Authentication protocols

- Key exchange protocols
Questions These Protocols *Might* Answer

Suppose $A$ completes a run of an authentication protocol, apparently with $B$; then what can $A$ deduce about $B$?

- $B$ has recently been alive?
- $B$ has recently been running the same protocol as $A$?
- $B$ thought he was running the protocol with $A$ (as opposed to some third party $C$)?
- $B$ thought $A$ initiated the protocol?
- $B$ agrees on the value of certain data items (e.g., keys)?
- $B$ agrees on the contents of all messages?
- There is a one-to-one correspondence between $B$’s runs and $A$’s (versus, e.g., that $A$ has completed more runs than $B$)?

A Hierarchy of Specifications

- **Aliveness**: If $A$ (acting as initiator) completes a run of the protocol, apparently with responder $B$, then $B$ was previously running the protocol.

- **Weak agreement**: If $A$ (acting as initiator) completes a run of the protocol, apparently with $B$, then $B$ was previously running the protocol, apparently with $A$. 
A Hierarchy of Specifications (cont.)

Let \( ds \) be a set of free variables in the protocol description.

- **Non-injective agreement**: If \( A \) (acting as initiator) completes a run of the protocol, apparently with responder \( B \), then
  - \( B \) was previously running the protocol, apparently with \( A \), and
  - \( B \) was acting as responder in this run, and
  - \( A \) and \( B \) agreed on the values corresponding to all variables in \( ds \).

- **Agreement**: If \( A \) (acting as initiator) completes a run of the protocol, apparently with responder \( B \), then
  - \( B \) was previously running the protocol, apparently with \( A \), and
  - \( B \) was acting as responder in this run, and
  - \( A \) and \( B \) agreed on the values corresponding to all variables in \( ds \), and
  - Each such run corresponds to a *unique* run of \( B \).

Adding Recentness (or Freshness)

- **Meaning of “recent” depends on the circumstances**
  - Within the duration of \( A \)'s run?
  - At most \( t \) time units before \( A \) completed her run?

- **Consider strengthening previous specifications to insist that \( B \)'s run was recent**
  - Recent aliveness
  - Recent weak agreement
  - Recent non-injective agreement
  - Recent agreement
Notation and Terminology

- **Session/run/round**
  - A sequence of messages between principals that constitute the beginning to the end of the protocol

- **Principals**
  - Alice (A) and Bob (B) are principals
  - Mike (M) is the adversary

- **Nonces**
  - A random number $N$, only used once ($Na$, a nonce generated by $A$)

- **Challenge response**
  - A message is sent (the “challenge”) which leads to a reply (the “response”) which could only have been produced with knowledge of the challenge

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Example of Challenge-Response

- Alice and Bob share a key $K_{ab}$
- Alice wishes to authenticate Bob

$A, E_{K_{ab}}(Na)$

$E_{K_{ab}}(Na + 1)$

Alice

Bob

- Alice is now convinced she’s talking to Bob
  - Should she be?
An “Attack”

- Alice and Bob share a key $K_{ab}$
- Alice wishes to authenticate Bob

Alice and Bob share a key $K_{ab}$

Alice thinks she is talking to Bob
In fact, she is talking to Mike (man-in-the-middle)
Is this an attack?

A More Fundamental Problem

- What is the role of encryption here?
Using the Right Primitive

- It is essential to use the right primitive for the right purpose
- Consider the following alternatives

\[
\begin{align*}
A, N_a & \overset{T_{Kab}(N_a)}{\rightarrow} \quad & T_{Kab}(N_a) & \rightarrow & A, N_a \\
A, E_{Kab}(N_a) & \overset{N_a}{\rightarrow} \quad & N_a & \rightarrow & A, E_{Kab}(N_a)
\end{align*}
\]

- These are better (maybe), but are they secure?

Adversary Models

- Passive Adversaries
  - Eavesdropping: can only listen to messages

- Active Adversaries
  - Replay (freshness attacks)
  - Insert (e.g., type flaw attacks, man-in-the-middle attacks)
  - Initiate different protocol sessions (parallel session attacks)
  - Delete (denial of service attacks)
Freshness Attacks

- A message from a previous run of a protocol is replayed as a message in the current run

\[ A, B, N_a \] → \[ A, B, N_a \] → \[ T_{Ka}(N_b) \]

\[ c_{ab}, c_b \] ← \[ c_{ab}, c_b \] ← \[ N_b \]

\[ t_a \leftarrow T_{Ka}(B, K_{ab}, N_a) \]
\[ c_a \leftarrow E_{ka}(B, K_{ab}, N_a, t_b) \]
\[ t_b \leftarrow T_{Ka}(A, K_{ab}) \]
\[ c_b \leftarrow E_{ka}(A, K_{ab}, t_b) \]

A variation on the Needham-Shroeder protocol

Freshness Attacks

- If an old \( K_{ab} \) is compromised

\[ A, B, N_a \] → \[ A, B, N_a \] → \[ T_{Ka}(N_b) \]

\[ c_{ab}, c_b \] ← \[ c_{ab}, c_b \] ← \[ N_b \]

\[ c_a \leftarrow E_{ka}(B, K_{ab}, N_a, t_b) \]
\[ t_b \leftarrow T_{Ka}(A, K_{ab}) \]
\[ c_b \leftarrow E_{ka}(A, K_{ab}, t_b) \]

- Bob will believe that he is talking to Alice
Freshness Attacks

- A fix for the previous protocol ... add a timestamp

\[ A, B, N_a \]

\[ \rightarrow \]

\[ c_a, c_b \]

\[ \leftarrow \]

\[ c_b \]

\[ \rightarrow \]

\[ N_b \]

\[ \rightarrow \]

\[ T_{K_{ab}}(N_b) \]

Alice

Bob

\[ t_a \leftarrow T_{K_{ab}}(B, K_{ab}, N_a) \]

\[ c_a \leftarrow E_{k_{ab}}(B, K_{ab}, N_a, t_a) \]

\[ t_b \leftarrow T_{K_{ab}}(A, K_{ab}) \]

\[ \tau \leftarrow \text{time()} \]

\[ c_b \leftarrow E_{k_{ab}}(A, K_{ab}, t_b, \tau) \]

Sherlock

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Freshness

- The freshness of messages must be inferred from some component of the message
- The component must be bound together with the rest of the message
  - Encryption is not a way to bind!
- Timestamps versus sequence numbers versus nonces
  - Unpredictable nonces are most useful
  - Timestamps require synchronized clocks
  - Sequence numbers are almost never the answer

Type Flaws

- A particular structure/type is exploited

  Alice: $A, E_{k_{ab}}(N_a)$
  Bob: $E_{k_{ab}}(N_a + 1, N_b)$

  Alice: $E_{k_{ab}}(N_b + 1)$
  Bob: $E_{k_{ab}}(k'_{ab}, N'_b)$

  Alice: $E_{k_{ab}}(N'_b + 1)$

- Alice and Bob both have the new session key $k'_{ab}$ and believe that the other person also holds $k'_{ab}$
Type Flaws

- If the nonces and keys are of the same length (e.g., 64 bits)

  A, $E_{kab}(N_a)$
  
  $E_{kab}(N_a + 1, N_b)$

  $E_{kab}(N_a + 1)$
  
  $E_{kab}(N_a + 1, N_b)$

  Mike can replay the message in step 2 in step 4
  Alice would accept $N_a + 1$ as the new session key
  Another demonstration of misused encryption ...

Parallel Session Attacks

- Two or more protocol sessions are executed concurrently
- Messages from one are used to form messages in another

  A, $N_a$
  
  $E_{kab}(N_a)$

  Alice concludes that Bob is operational currently
Parallel Session Attacks

Mike initiated round 2, and Alice acts as the oracle that provides the right answer for round 1.

Parallel Session Attacks

Alice asks for Bob’s public key.

Sherlock replies in step 2.

There is nothing in Sherlock’s response that ties $k_b$ to $B$. 

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Parallel Session Attacks

- Mike initiates a different session with Sherlock in which Sherlock serves as the Oracle
- Sherlock’s answer in the second session is used to complete the first session with Alice
- Alice is convinced that she now has Bob’s public key, while the key she has is Mike’s public key

Parallel Session Attacks (A fix)

- Signature binds “B” and the rest of the message
- Other fixes?
Some Engineering Principles

- Every message should explicitly say what it means.
- If the identity of a principal is essential to the meaning of a message, then mention the principal’s name explicitly in the message.
- Use the right primitive for the job.
  - Encryption is for secrecy, nothing else!
- When a principal signs material that has already been encrypted, it should not be inferred that the principal knows the content of the message.
- A key may have been used recently, for example to tag a nonce, and yet be quite old and possibly compromised. Recent use does not mean the key is fresh.

Passwords as Long-Term Secrets

- Often in key exchange protocols, long-term keys are generated from human-input secrets (passwords)
  - This is extremely dangerous if not done carefully
- It is well-known that humans tend to choose passwords from a relatively small fraction of all possible passwords
  - $> 2 \times 10^8$ 8-character passwords consisting of upper and lower case letters and numbers alone
  - Yet, “dictionary attacks” of several million common words frequently yield a significant number of passwords
- A single password-encrypted message can expose the password to dictionary attacks
  - Entirely different protocols are needed here
Summary

- Protocol design and implementation is anything but simple
- Flaws can be subtle and difficult to eliminate
- There is a pressing need for the rigorous analysis and development of security protocols