Reusing Static Keys in Key Agreement Protocols

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To Reuse or Not To Reuse

Robustness principles for public key protocols:

> *If possible avoid using the same key for two different purposes (such as signing and decryption) ...*

Handbook of Applied Cryptography:

> *The principle of* key separation *is that keys for different purposes should be cryptographically separated.*

But reuse can be beneficial!

- Cost effective
- Efficient

Reuse: Pitfalls

- Kelsey, Schneier and Wagner [1998]
  - *Chosen protocol attack:* Design a new protocol to attack an existing protocol when the keying material is shared.
- Gligoroski, Andova and Knapskog [2008]
  - Using the same key for CBC and OFB/CTR mode of operation can be detrimental.

Reuse: Not Necessarily Bad

- Coron et al. [2002]
  - RSA key pairs can be reused for PSS versions of signature and encryption.
- Vasco et al. [2008]
  - Boneh-Franklin IBE and Hess's Id-based signature.
  - Pointcheval-Stern version of ElGamal signature and ElGamal encryption with Fujisaki-Okamoto conversion.

What's NIST saying

A static key pair may be used in more than one key establishment scheme. However, one static public/private key pair **shall not** *be used for different purposes (for example, a digital signature key pair is not to be used for key establishment or vice versa) with the following possible exception: when requesting the (initial) certificate for a public static key establishment key, the key establishment private key associated with the public key may be used to sign certificate request.*

NIST SP 800-56A, March, 2007

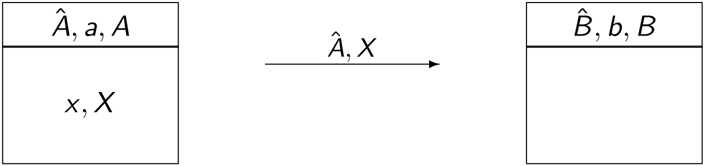
The Setting

- Variants of Diffie-Hellman protocol.
- $G = \langle g \rangle$: cyclic group of prime order q.
- $\hat{A}$: *Initiator* ($\mathcal{I}$)
  - Static key pair: $(a \in_R \mathbb{Z}_q^*, A = g^a)$
  - Ephemeral key pair: $(x \in_R \mathbb{Z}_q^*, X = g^x)$
- $\hat{B}$: *Responder* ($\mathcal{R}$)
  - Static key pair: $(b,\ B)$
  - Ephemeral key pair: (y, Y)
- CA: Issues certificates binding a party's identifier to its static public key.

Unified Model

- Family of two-party Diffie-Hellman key agreement protocols.
- Standardized in ANSI X9.42, ANSI X9.63, NIST SP 800-56A.

One-pass Unified Model



$$\kappa_1 = H(g^{xb}, g^{ab}, \mathrm{keydatalen}, \mathrm{AlgorithmID}, \hat{A}, \hat{B}, \Lambda)$$

- **keydatalen:** Bitlength of secret keying material to be generated.
- **AlgorithmID:** How the derived keying material will be parsed and for which algorithm(s) it will be used
- Λ: Optional public information.

Three-pass Unified Model

Two pass protocol combined with bilateral key confirmation.

$\hat{A}, a, A$		$\hat{B}, b, B$
x, X	$\xrightarrow{\hat{A}, X}$	y, Y
	$\xleftarrow{\hat{B}, Y, T_B = \mathrm{MAC}_{\kappa'}(\mathcal{R}, \hat{B}, \hat{A}, Y, X, \Lambda_1)}$	
	$\xrightarrow{T_A = \mathrm{MAC}_{\kappa'}(\mathcal{I}, \hat{A}, \hat{B}, X, Y, \Lambda_2)}$	

$$(\kappa', \ \kappa_2) = H(g^{xy}, g^{ab}, \text{keydatalen}, \text{AlgorithmID}, \hat{A}, \hat{B}, \Lambda)$$

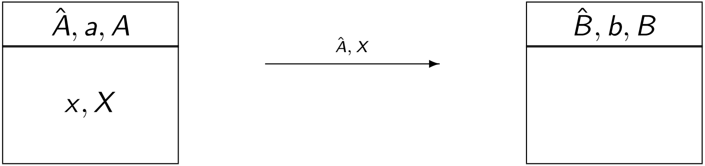
- $\Lambda_1, \ \Lambda_2$: Optional public strings
- κ_2 : Session key
- κ' : Ephemeral secret key

The Backdrop

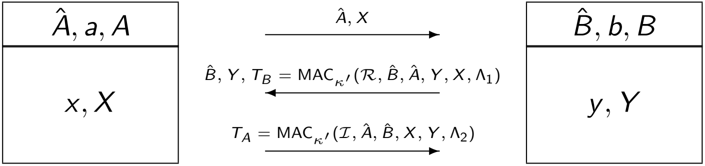
- One-pass protocol is used to derive 256 bits session key $\kappa_1 = (\kappa_m,\ \kappa_e)$.
  - κ_m : 128 bit HMAC key
  - κ_e : 128-bit AES key
- Three-pass protocol uses HMAC with 128-bit κ' and produces 128-bit session key κ_2.
- Attacker is able to use a SessionKeyReveal to obtain session keys produced by the one-pass protocol.
- Both protocols use same AlgorithmID.

NIST SP 800-56A:

> AlgorithmID *might indicate that bits* $1 - 80$ *are to be used as an* 80-*bit HMAC key and that bits* $81 - 208$ *are to be used as a* 128-*bit AES key.*



$$\kappa_1 = H(g^{xb}, g^{ab}, \text{keydatalen}, \text{AlgorithmID}, \hat{A}, \hat{B}, \Lambda)$$



$$(\kappa', \ \kappa_2) = H(g^{xy}, g^{ab}, \text{keydatalen}, \text{AlgorithmID}, \hat{A}, \hat{B}, \Lambda)$$

The Attack

1. $\mathcal{M}$ initiates a session sid_1 of three-pass UM at $\hat{A}$; receives $(\hat{A}, X)$.
2. $\mathcal{M}$ forwards $(\hat{A}, X)$ to $\hat{B}$ in a session sid_2 of one-pass UM.
3. $\hat{B}$ computes session key κ_2 following one-pass UM.
4. $\mathcal{M}$ issues a *SessionKeyReveal* to sid_2 at $\hat{B}$ to obtain $\kappa_1 = (\kappa_m,\ \kappa_e)$.
5. $\mathcal{M}$ sets $Y = B$, so $\kappa_1 = (\kappa',\ \kappa_2)$ under our assumptions. $\mathcal{M}$ computes T_B, sends $(\hat{B}, Y, T_B)$ to session sid_1 at $\hat{A}$.
6. $\hat{A}$ computes κ_2 in sid_1 which is known to $\mathcal{M}$.

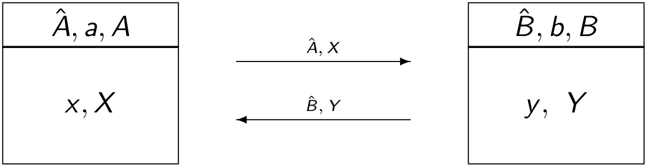
Same attack can be launched against three-pass MQV when static keys are reused with one-pass MQV.

KEA+h Protocol

KEA: Autheticated key exchange protocol; introduced by NSA.

KEA+: Modification of KEA; introduced by Lauter-Mityagin [PKC2006].

KEA+h: Modification of KEA+.



$$\kappa = H(H_1(g^{ay}), H_1(g^{bx}), \hat{A}, \hat{B})$$

τ-Protocol

A new protocol.

Uses an MTI/C0-like exchange of messages to confirm the receipt of ephemeral public keys.

Can be proven secure in the Canetti-Krawczyk model.

$$
\begin{array}{|c|}\hline \hat{A}, a, A \\ \hline x, X \\ \hline \end{array}
\quad
\begin{array}{c}
\xrightarrow{\hat{A},\, X,\, T_A = H_2(g^{ab}, X, \hat{A}, \hat{B}, \mathcal{I})} \\
\xleftarrow{\hat{B},\, Y,\, T_B = H_2(g^{ab}, Y, \hat{B}, \hat{A}, \mathcal{R}),\, \overline{X} = H_1(X^b)} \\
\xrightarrow{\overline{Y} = H_1(Y^a)}
\end{array}
\quad
\begin{array}{|c|}\hline \hat{B}, b, B \\ \hline y, Y \\ \hline \end{array}
$$

$$\kappa = H(g^{xy},\ X,\ Y)$$

The Scenario

- Attack a KEA+h session using τ-protocol.
- $\hat{A}$ uses the KEA+h protocol in a stand-alone setting.
- $\hat{B}$ uses the same static key for KEA+h and τ.
- $\hat{A}$ initiates a KEA+h session with $\hat{B}$.
- $\hat{A}$ ends up getting her session key compromised.

$\hat{A}, a, A$		$\hat{B}, b, B$
x, X	$\xrightarrow{\hat{A}, X}$ $\xleftarrow{\hat{B}, Y}$	y, Y

$$\kappa = H(H_1(g^{ay}), H_1(g^{bx}), \hat{A}, \hat{B})$$

$\hat{A}, a, A$		$\hat{B}, b, B$
x, X	$\xrightarrow{\hat{A}, X, T_A = H_2(g^{ab}, X, \hat{A}, \hat{B}, \mathcal{I})}$ $\xleftarrow{\hat{B}, Y, T_B = H_2(g^{ab}, Y, \hat{B}, \hat{A}, \mathcal{R}), \overline{X} = H_1(X^b)}$ $\xrightarrow{\overline{Y} = H_1(Y^a)}$	y, Y

$$\kappa = H(g^{xy}, X, Y)$$

The Attack

1. $\mathcal{M}$ initiates a KEA+h session at $\hat{A}$ with $\hat{B}$ as the peer and obtains the outgoing ephemeral public key X.
2. $\mathcal{M}$ controls a party $\hat{E}$ with static key pair $(e,\ E = g^e)$ and initiates a τ session with $\hat{B}$ by sending the message $X, T_E = \left(H_2(B^e, X, \hat{E}, \hat{B}, \mathcal{I})\right)$
3. $\hat{B}$ responds with $(Y, T_B, H_1(X^b))$ from which $\mathcal{M}$ obtains $H_1(X^b)$.
4. $\mathcal{M}$ selects an ephemeral key pair $(z, Z = g^z)$ and sends $(\hat{B},\ Z)$ to $\hat{A}$ in KEA+h.
5. $\hat{A}$ computes the KEA+h session key as $\kappa = H\left(H_1(Z^a), H_1(B^x), \hat{A}, \hat{B}\right)$.
6. $\mathcal{M}$ computes the same session key as $\kappa = H\left(H_1(A^z), H_1(X^b), \hat{A}, \hat{B}\right)$.

"Shared" Model

- To capture the security assurances guaranteed by two (or more) distinct key agreement protocols.
- Each party uses same static key pair in all the protocols.
- Individual protocols are two-party Diffie-Hellman variety.
- Enhances the extended Canetti-Krawczyk model.
  - $\Pi_1,\ \Pi_2, \ldots, \Pi_d$ are run concurrently by a party.
  - Same static key is reused for all the protocols.
  - Π_i provides the security attributes implied by the eCK model.

Security Model

Essential idea: add a protocol identifier

- Protocol message: $(\Pi_i,\ \hat{A},\ \hat{B},\ \mathit{role},\ \mathit{Comm})$.
- Session identifier: $(\Pi_i,\ \hat{A},\ \hat{B},\ \mathit{role},\ \ldots)$.

Matching session

- $\mathit{sid} = (\Pi_i, \hat{A},\ \hat{B},\ \mathit{role}_A, \mathit{Comm}_A)$
- $\mathit{sid}^* = (\Pi_j, \hat{C},\ \hat{D},\ \mathit{role}_C, \mathit{Comm}_C)$
- *matching* if $\Pi_i = \Pi_j,\ \hat{A} = \hat{D},\ \hat{B} = \hat{C},\ \mathit{role}_A \neq \mathit{role}_C$ and $\mathit{Comm}_A \equiv \mathit{Comm}_C$

Adversary

Modeled as a probabilistic Turing machine $\mathcal{M}$ and controls *all* communications.

$\mathcal{M}$ can make the following queries:

- StaticKeyReveal($\hat{A}$)
- *EphemeralKeyReveal*(*sid*)
- *SessionKeyReveal*(*sid*)
- *EstablishParty*($\hat{A}$, A)
    - To model attacks by malicious insiders.
    - Parties established by $\mathcal{M}$ are *corrupted*.
    - A party not corrupted is *honest*.

Adversary's Goal

- $\mathcal{M}$ is allowed to make a special query *Test*(*sid*) to a 'fresh' session *sid*.
- $\mathcal{M}$ is given with equal probability either the session key of *sid* or a random key.
- $\mathcal{M}$ wins if its guess is correct.
- $\mathcal{M}$ can continue interacting with the parties after issuing the *Test* query, but the test session must remain fresh.

Π-fresh

- *sid*: A completed Π-session; owner $\hat{A}$, peer $\hat{B}$: both honest.
- sid^*: Matching session of *sid*, if exists.
- *sid* is Π-fresh if *none* of the following conditions hold:
  1. $\mathcal{M}$ issued *SessionKeyReveal*(*sid*) or *SessionKeyReveal*(sid^*).
  2. (sid^*) exists and $\mathcal{M}$ issued one of the following:
     2.1 Both *StaticKeyReveal*($\hat{A}$) and *EphemeralKeyReveal*(*sid*).
     2.2 Both *StaticKeyReveal*($\hat{B}$) and *EphemeralKeyReveal*(sid^*).
  3. (sid^*) does not exist and $\mathcal{M}$ issued one of the following:
     3.1 Both *StaticKeyReveal*($\hat{A}$) and *EphemeralKeyReveal*(*sid*).
     3.2 *StaticKeyReveal*($\hat{B}$).

Security in Shared Model

$\Pi_1, \Pi_2, \ldots, \Pi_d$: *secure in the shared model if the following conditions hold:*

1. *If two honest parties complete matching Π_i-sessions then, except with negligible probability, they both compute the same session key.*
2. *No $\mathcal{M}$ can distinguish the session key of a fresh Π_i-session from a randomly chosen session key, with probability greater than $\frac{1}{2}$ plus a negligible fraction.*

NAXOS-C

$\hat{A}, a, A$		$\hat{B}, b, B$
$\tilde{x}, X = g^{H_1(a,\ \tilde{x})}$	$\xrightarrow{\hat{A}, X}$	$\tilde{y}, Y = g^{H_1(b, \tilde{y})}$
	$\xleftarrow{\hat{B},\ Y,\ T_B = H_2(\kappa_m,\ \mathcal{R}, \hat{B}, \hat{A}, Y, X, \Pi_1)}$	
	$\xrightarrow{\hat{A},\ T_A = H_2(\kappa_m,\ \mathcal{I}, \hat{A}, \hat{B}, X, Y, \Pi_1)}$	

$$(\kappa_m,\ \kappa) = H(g^{ay},\ g^{bx},\ \hat{A}, \hat{B}, X, Y, \Pi_1)$$

- $H : \{0,\ 1\}^* \to \{0,\ 1\}^\gamma \times \{0,\ 1\}^\gamma$
- $H_1 : \{0,\ 1\}^* \to [0,\ q-1]$
- $H_2 : \{0,\ 1\}^* \to \{0,\ 1\}^{2\gamma}$

DHKEA

$\hat{A}, a, A$		$\hat{B}, b, B$
$\tilde{x}, X = g^{H_1(a,\ \tilde{x})}$	$\xrightarrow{\hat{A},\, X}$	$\tilde{y}, Y = g^{H_1(b, \tilde{y})}$
	$\xleftarrow{\hat{B},\, Y,\, T_B \,=\, H_2(\kappa_m,\ g^{bx},\ \mathcal{R}, \hat{B}, \hat{A}, Y, X, \Pi_2)}$	
	$\xrightarrow{\hat{A},\ T_A \,=\, H_2(\kappa_m,\ g^{ay},\ (\mathcal{I}, \hat{A}, \hat{B}, X, Y, \Pi_2)}$	

$$(\kappa_m,\ \kappa) = H(g^{xy},\ \hat{A}, \hat{B}, X, Y, \Pi_2)$$

- $H : \{0,\ 1\}^* \rightarrow \{0,\ 1\}^\gamma \times \{0,\ 1\}^\gamma$
- $H_1 : \{0,\ 1\}^* \rightarrow [0,\ q-1]$
- $H_2 : \{0,\ 1\}^* \rightarrow \{0,\ 1\}^{2\gamma}$

Conclusion

- Vulnerabilty of KA protocols when static key is reused.
- Security model for KA protocols allowing such reuse.

Our shared model assumes each party has exactly one static key pair.

Further refinements:

1. Each party having mutiple static key pairs.
2. Protocols having different security attributes.

What's your conclusion?