A Computational Security Analysis of Signal's PQXDH Handshake

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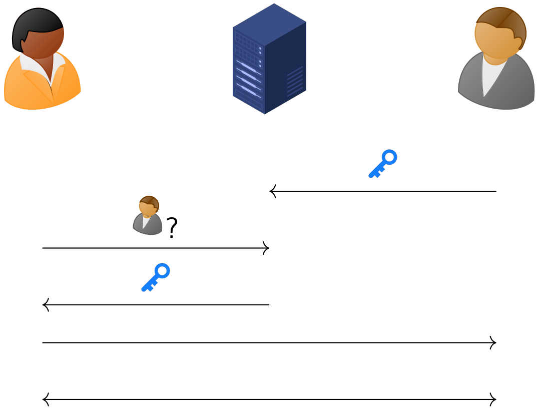
Asynchronous Authenticated Key Exchange



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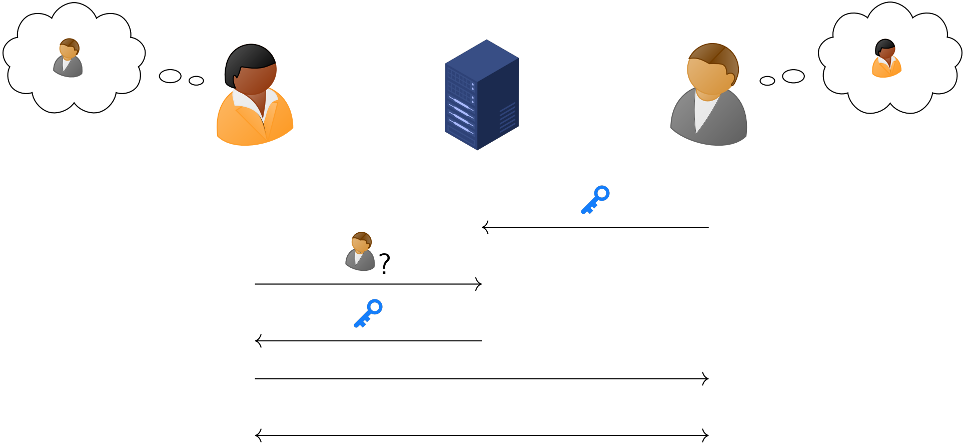

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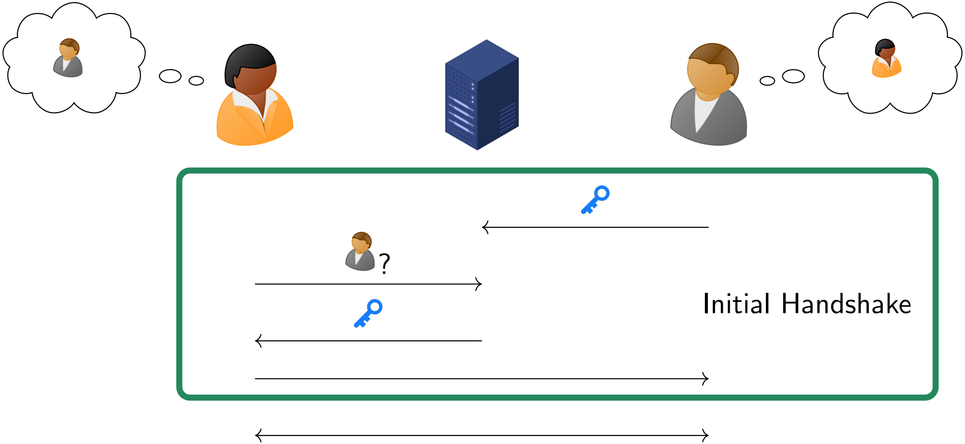
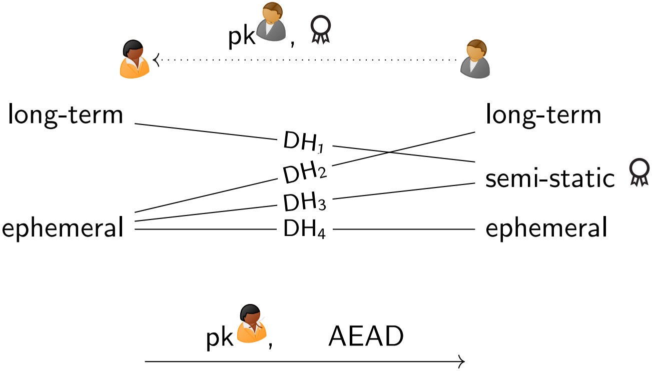


Signal's Initial Handshake(s): X3DH and PQXDH



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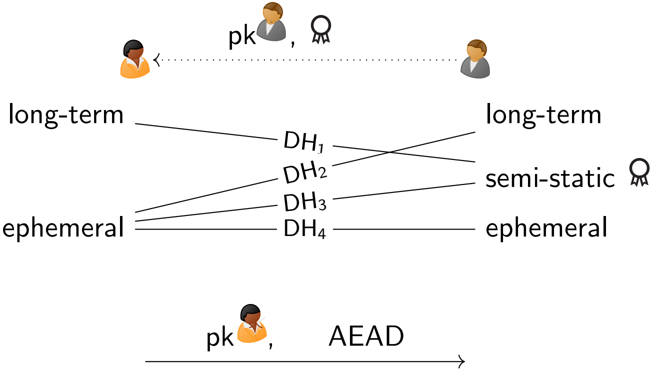

pk,

long-term

ephemeral

DH$_1$

DH$_2$

DH$_3$

DH$_4$

long-term

semi-static

ephemeral

pk, AEAD

- session key: $\mathrm{KDF}(\mathrm{DH}_1 \| \ldots \| \mathrm{DH}_4 \quad)$

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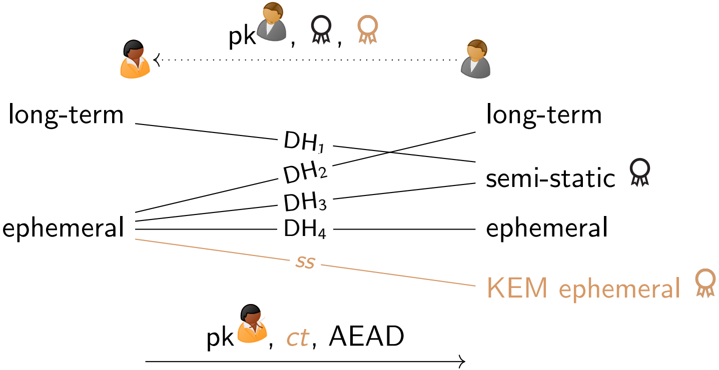

pk, ,

long-term

long-term

DH₁

DH₂

semi-static

DH₃

ephemeral

DH₄

ephemeral

ss

KEM ephemeral

pk, *ct*, AEAD

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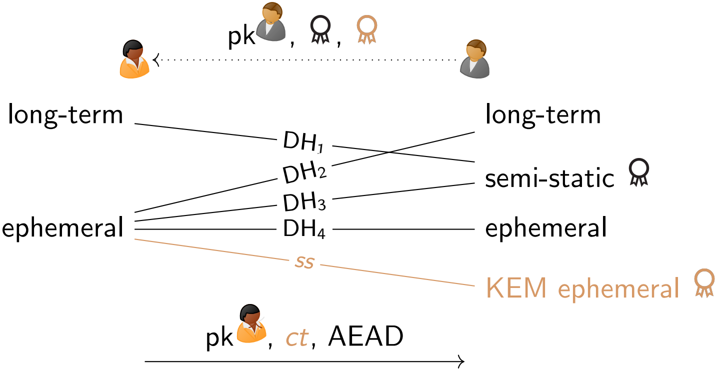

pk, ,

long-term

long-term

DH_1

DH_2

semi-static

DH_3

ephemeral

DH_4

ephemeral

ss

KEM ephemeral

pk, *ct*, AEAD

- session key: $\mathrm{KDF}(\mathrm{DH}_1 \| \ldots \| \mathrm{DH}_4 \| ss)$
- reduced session: Bob without ephemeral keys, semi-static KEM

Analyzing Signal's Initial Handshake(s): X3DH and PQXDH

- reductionist analysis of X3DH [CCD$^+$17] with a [BR94] style key exchange model
- tool-based analysis of PQXDH with ProVerif and CryptoVerif [BJK23, BJKS23]
  - (re-)discovered (potential) KEM re-encapsulation attack [CDM23]
  - corruption of long-term keys only

[BJK23, BJKS23] Barghavan, Jacomme, Kiefer, Schmidt, 2023
[BR94] Bellare, Rogaway, CRYPTO 1993
[BFG$^+$22] Brendel, Fiedler, Günther, Janson, Stebila, PKC 2022
[CCD$^+$17] Cohn-Gordon, Cremers, Dowling, Garratt, Stebila, EuroSP 2017
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[FG24] Fiedler, Günther, ePrint 2024

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  - corruption of long-term keys only
- our work: [FG24]
  - follows [CCD+17, BFG+22] but explicitly models signatures (albeit with distinct signing keys)
  - identifies precise requirements of the KEM
  - models maximum-exposure w. clean predicates: $\underbrace{\underbrace{\underbrace{\mathsf{clean}_{\mathsf{LTSS}}, \mathsf{clean}_{\mathsf{ELT}}, \mathsf{clean}_{\mathsf{ESS}}}_{\text{reduced}}, \mathsf{clean}_{\mathsf{EE}}}_{\text{X3DH full}}, \mathsf{clean}_{\mathsf{sigE}}}_{\text{PQXDH full}}$

[BJK23, BJKS23] Barghavan, Jacomme, Kiefer, Schmidt, 2023
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Concrete Bound for PQXDH

$$
\begin{aligned}
\mathsf{Adv}^{\mathsf{KI}}_{\mathsf{PQXDH}}(\mathcal{A}) \leq{}& \frac{(n_p + n_p \cdot n_{ss} + n_s)^2}{q} + \gamma_{\mathsf{coll}}(n_p \cdot n_{ss} + n_s) + n_s \cdot \delta_{\mathsf{corr}} + \epsilon_{LEAK^+} \\
&+ \left(\begin{array}{ll}
\quad (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_p \cdot n_{ss} \cdot \epsilon_{\mathsf{GDH}})) & /\!/\ \mathsf{clean}_{\mathsf{LTSS}} \\
+ (n_s \cdot n_p \cdot \epsilon_{\mathsf{GDH}}) & /\!/\ \mathsf{clean}_{\mathsf{ELT}} \\
+ (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \epsilon_{\mathsf{GDH}})) & /\!/\ \mathsf{clean}_{\mathsf{ESS}} \land \mathsf{type} = \mathsf{full} \\
+ (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon_{\mathsf{CCA}}))) & /\!/\ \mathsf{clean}_{\mathsf{ESS}} \land \mathsf{type} = \mathsf{reduced} \\
+ \left(n_s^2 \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon_{\mathsf{CCA}})\right) & /\!/\ \mathsf{clean}_{\mathsf{EE}} \land \mathsf{clean}_{\mathsf{peerE}} \\
+ \left(n_p \cdot \left(\epsilon_{\mathsf{SIG}} + n_s^2 \cdot q_{\mathrm{RO}} \cdot \epsilon_{\mathsf{CCA}}\right)\right) & /\!/\ \mathsf{clean}_{\mathsf{EE}} \land \mathsf{clean}_{\mathsf{sigE}}
\end{array} \right)
\end{aligned}
$$

Concrete Bound for PQXDH

$$
\mathsf{Adv}^{\mathsf{KI}}_{\mathsf{PQXDH}}(\mathcal{A}) \leq \frac{(n_p + n_p \cdot n_{ss} + n_s)^2}{q} + \gamma_{\mathsf{coll}}(n_p \cdot n_{ss} + n_s) + n_s \cdot \delta_{\mathsf{corr}} + \epsilon_{LEAK^+}
$$

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+ \left(\begin{array}{ll}
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KEM Re-Encapsulation Attack [CDM23, BJK23, BJKS23]

- two sessions with same DH public keys, distinct KEM keys, both reduced

$\ldots, ct$

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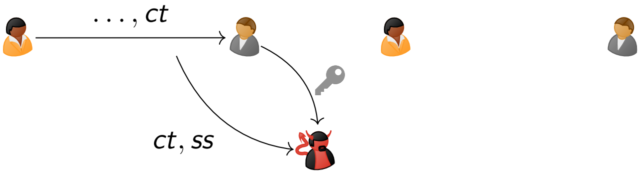

$\ldots, ct$

ct, ss

re-encapsulate
ss into ct'

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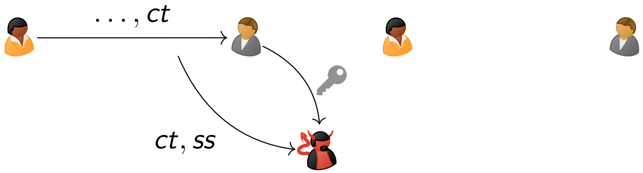

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$\underline{KEM.encaps(\mathsf{pk}):}$
$ss \leftarrow \{0,1\}^{256}$
$ct \leftarrow PKE.encrypt(\mathsf{pk}, ss)$
$\textbf{return } (ct, ss)$
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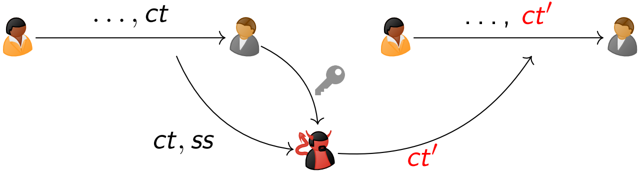

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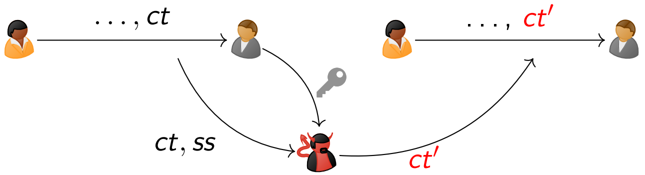

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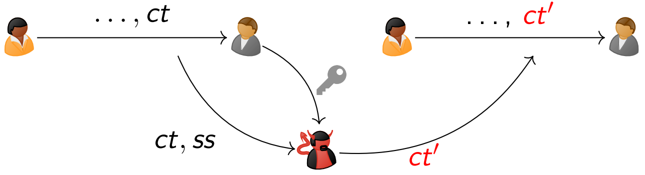

$\ldots, ct$

$\ldots, ct'$

ct, ss

ct'

re-encapsulate

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session key: $\mathrm{KDF}(\mathrm{DH}_1 \| \ldots \| \mathrm{DH}_4 \| ss)$

- $\Rightarrow$ two sessions with same session key: adversary can reveal one and test the other
- [BJK23, BJKS23] models the KEM public key into the Associated Data of the AEAD
- which KEM property needed?
- proposed protocol fix: session context (KEM public key, ciphertext) in key derivation

KEM Binding Notion $LEAK^{+}$-BIND-SS-$\{CT, PK\}$ (extending [CDM23])

$$((\mathrm{pk}, \mathrm{sk}, r)_1, \ldots, (\mathrm{pk}, \mathrm{sk}, r)_n)$$

$$(\mathrm{pk}_i, ct_i) \neq (\mathrm{pk}_j, ct_j)$$

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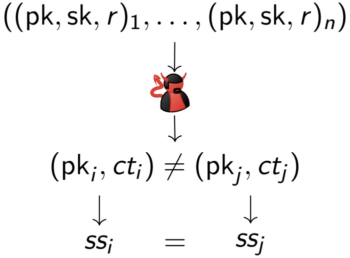

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$ss_i = ss_j$

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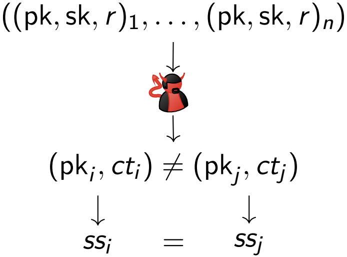

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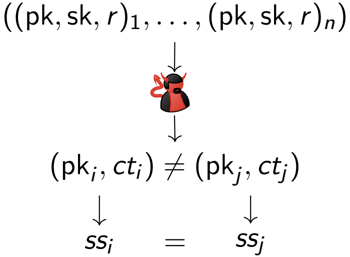

$$\begin{tikzcd}
((\mathrm{pk},\mathrm{sk},r)_1,\ldots,(\mathrm{pk},\mathrm{sk},r)_n) \arrow[d] \\
\text{} \arrow[d] \\
(\mathrm{pk}_i, ct_i) \neq (\mathrm{pk}_j, ct_j)
\end{tikzcd}$$

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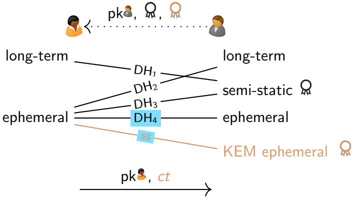
ss_i & = & ss_j
\end{tikzcd}$$

$$\begin{tikzcd}
\mathit{MAL}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[d, bend left] \\
\mathit{LEAK}^{+}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[u, bend left, "/" marking, "\text{ML-KEM}"] \arrow[d, bend left] \\
\mathit{LEAK}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[u, bend left, "/" marking]
\end{tikzcd}$$

Concrete Hybrid Bound for PQXDH

$$\mathsf{Adv}^{\mathsf{KI}}_{\mathsf{PQXDH}}(\mathcal{A}) \leq \frac{(n_p + n_p \cdot n_{ss} + n_s)^2}{q} + \gamma_{\mathsf{coll}}(n_p \cdot n_{ss} + n_s) + n_s \cdot \delta_{\mathsf{corr}} + \epsilon_{LEAK^+}$$

$$+ \left(\begin{array}{ll} \quad (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_p \cdot n_{ss} \cdot \epsilon_{\mathsf{GDH}})) & /\!/ \text{ clean}_{\mathsf{LTSS}} \\ + (n_s \cdot n_p \cdot \epsilon_{\mathsf{GDH}}) & /\!/ \text{ clean}_{\mathsf{ELT}} \\ + (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \epsilon_{\mathsf{GDH}})) & /\!/ \text{ clean}_{\mathsf{ESS}} \wedge \text{type} = \text{full} \\ + (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon_{\mathsf{CCA}}))) & /\!/ \text{ clean}_{\mathsf{ESS}} \wedge \text{type} = \text{reduced} \\ + (n_s^2 \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon_{\mathsf{CCA}})) & /\!/ \text{ clean}_{\mathsf{EE}} \wedge \text{clean}_{\mathsf{peerE}} \\ + (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_s^2 \cdot q_{\mathrm{RO}} \cdot \epsilon_{\mathsf{CCA}})) & /\!/ \text{ clean}_{\mathsf{EE}} \wedge \text{clean}_{\mathsf{sigE}} \end{array} \right)$$



Concrete Bound for PQXDH Against Active-Later-Quantum Adversaries

$$\mathsf{Adv}^{\mathsf{KI}}_{\mathsf{PQXDH}}(\mathcal{A}) \le \frac{(n_p + n_p \cdot n_{ss} + n_s)^2}{q} + \gamma_{\mathsf{coll}}(n_p \cdot n_{ss} + n_s) + n_s \cdot \delta_{\mathsf{corr}} + \epsilon_{LEAK^+}$$

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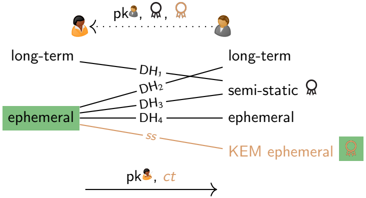
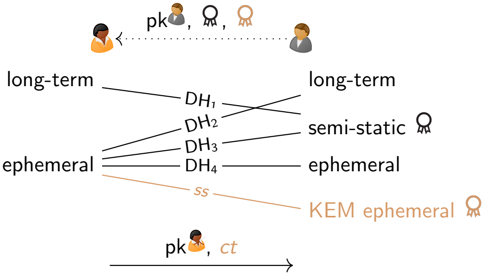


PQXDH Provides Hybrid Security



$$\begin{tikzcd} \mathit{MAL}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[d, shift left] \\ \mathit{LEAK}^{+}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[u, shift left, "\text{ML-KEM}", "/" marking] \arrow[d, shift left] \\ \mathit{LEAK}\text{-BIND-}\mathit{SS}\text{-}\{\mathit{CT},\mathit{PK}\} \arrow[u, shift left, "/" marking] \end{tikzcd}$$

or include the session context in key derivation

$$\mathsf{Adv}^{\mathsf{KI}}_{\mathsf{PQXDH}}(\mathcal{A}) \le \frac{(n_p + n_p \cdot n_{ss} + n_s)^2}{q} + \gamma_{\mathsf{coll}}(n_p \cdot n_{ss} + n_s) + n_s \cdot \delta_{\mathsf{corr}} + \epsilon_{LEAK^+}$$

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combine tool-based and reductionist analyses

⇒ detect attacks and identify requirements

`https://eprint.iacr.org/2024/702`

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References I

[BFG$^+$22] Jacqueline Brendel, Rune Fiedler, Felix Günther, Christian Janson, and Douglas Stebila.
Post-quantum asynchronous deniable key exchange and the Signal handshake.
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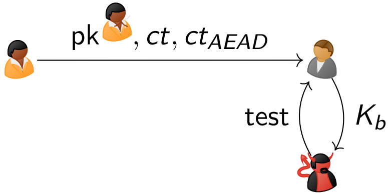
Picture References

- server icon by Alexiuz AS
- public key icon by Yannick Lung
- secret key icon by Yannick Lung
- signature icon by PINPOINT.WORLD

What if we model the AEAD ciphertext?



```
if $AEAD.Dec(K_b, ct_{AEAD}) \neq \perp$ : return 0
else return 1
```

- $\Rightarrow$ adversary trivially wins (except with negligible probability)