Security Analysis of Signal's PQXDH Handshake

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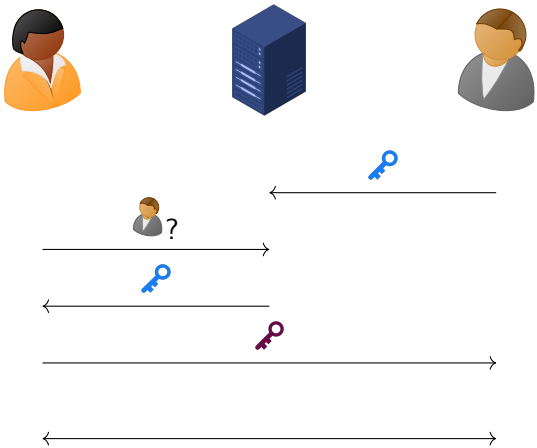
Signal: Asynchronous Authenticated Key Exchange



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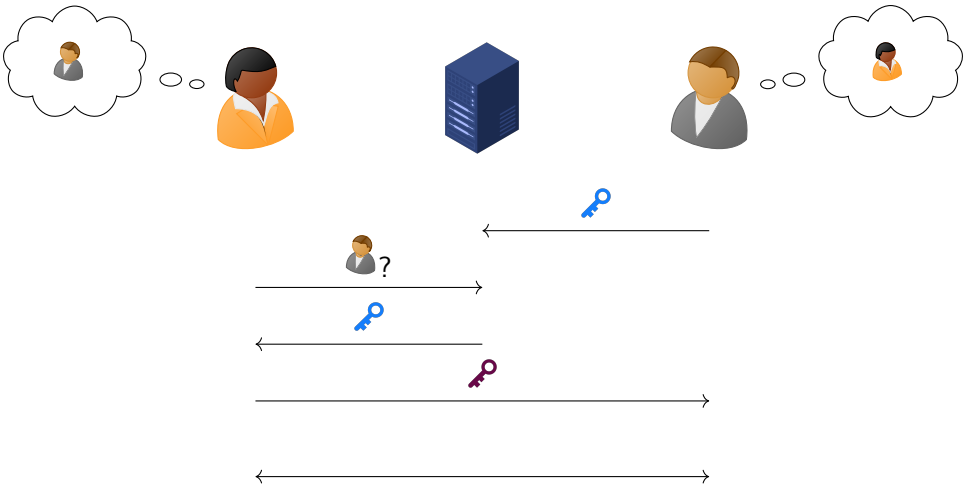

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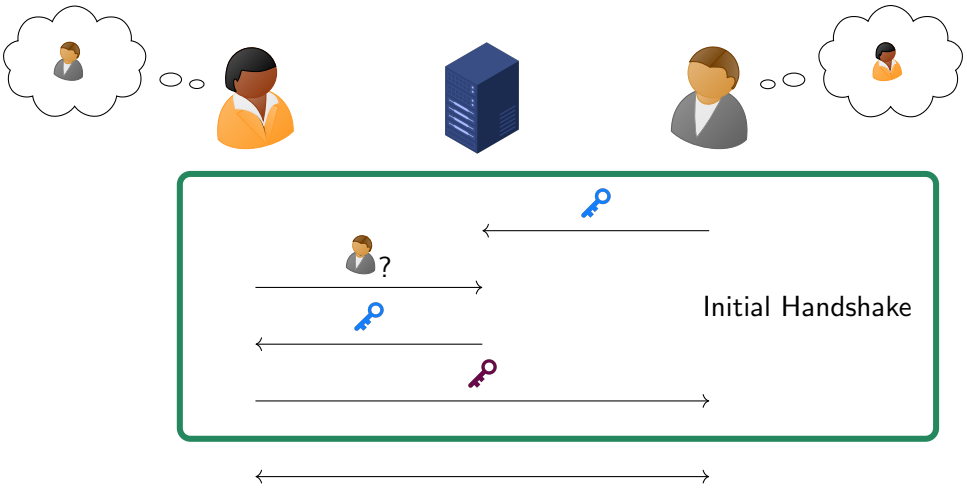
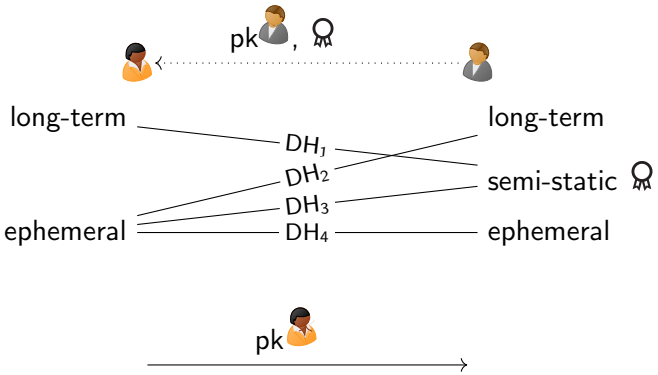


Signal's Initial Handshake(s): X3DH and PQXDH



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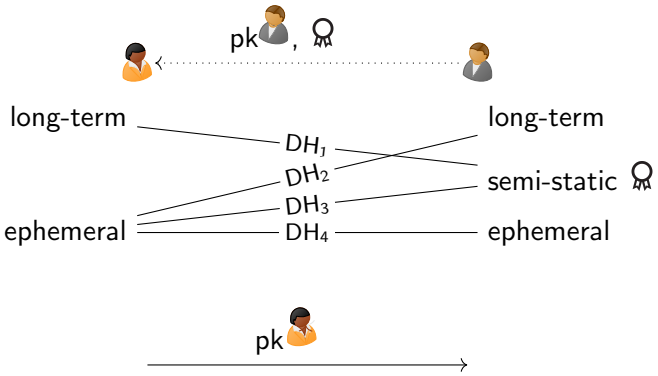

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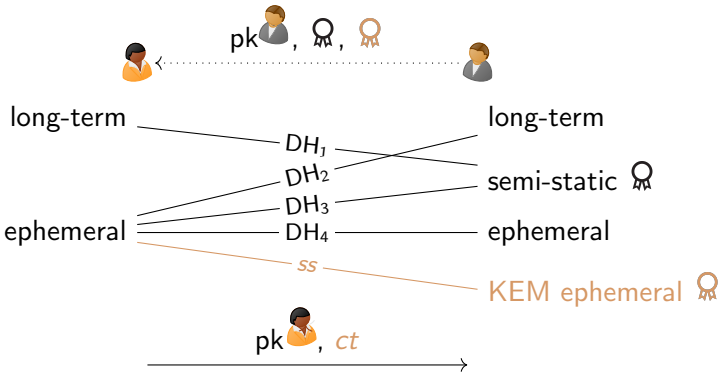

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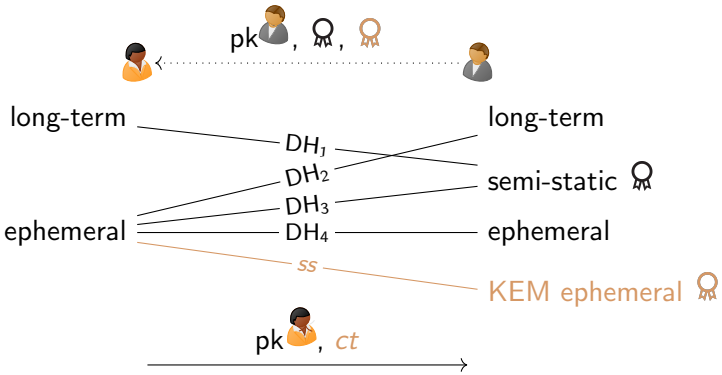

- session key: $\mathrm{KDF}(\mathrm{DH}_1 \| \ldots \| \mathrm{DH}_4 \| ss)$
- reduced session: Bob without ephemeral keys, semi-static KEM

Analyses of 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 [BJKS24]
  - (re-)discovered (potential) KEM re-encapsulation attack [CDM24]
  - corruption of long-term keys only
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- our work
  - follows [CCD+17, BFG+22] but explicitly models signatures (albeit with distinct signing keys)
  - identifies precise requirements of the KEM
  - models maximum-exposure with clean predicates

Concrete Bound for PQXDH against classical adversaries

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

$$
\begin{aligned}
&+ \left(n_p \cdot (\epsilon_{\mathrm{SIG}} + n_p \cdot n_{ss} \cdot \epsilon_{\mathrm{GDH}})\right) && /\!/\ \mathrm{clean}_{\text{LT-SS}} \\
&+ \left(n_s \cdot n_p \cdot \epsilon_{\mathrm{GDH}}\right) && /\!/\ \mathrm{clean}_{\text{E-LT}} \\
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- two sessions with same DH public keys, distinct KEM keys, both reduced

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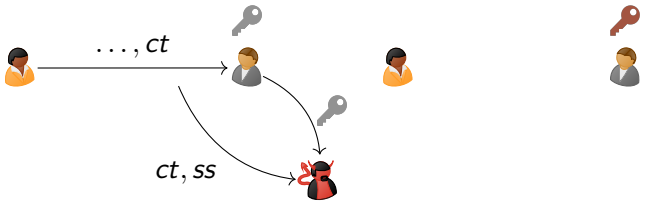

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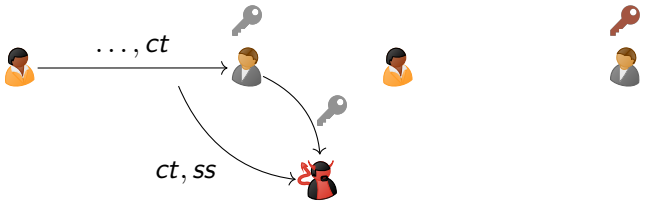

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$ss \leftarrow \{0,1\}^{256}$
$ct \leftarrow PKE.encrypt(\mathrm{pk}, ss)$
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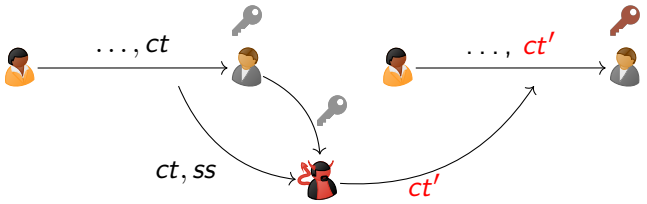

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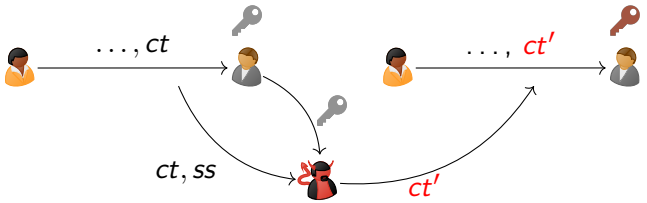

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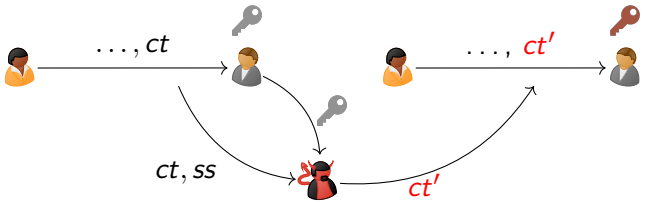

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- $\Rightarrow$ two sessions with same session key: adversary can reveal one and test the other
- proposed protocol fix: session context (KEM public key, ciphertext) in key derivation
- which KEM property needed?

KEM Binding Notion $LEAK^{+r}$-BIND-SS-$\{CT, PK\}$ (extending [CDM24])

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

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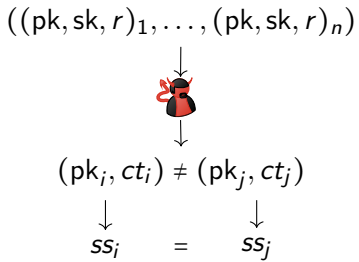

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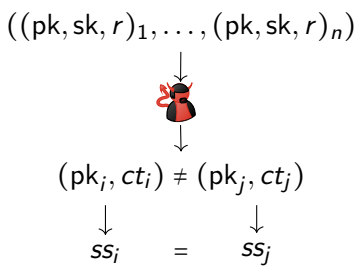

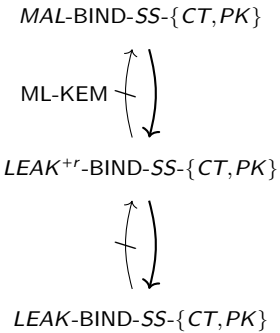

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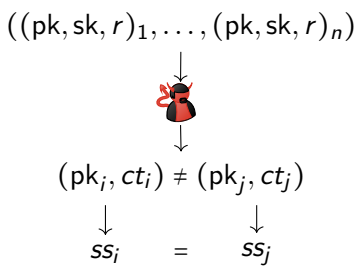

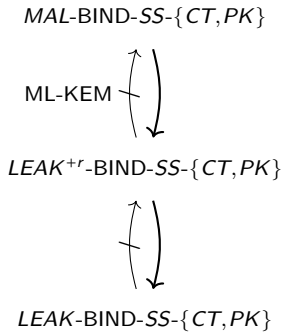

Signal: Kyber ✓
ML-KEM ✓

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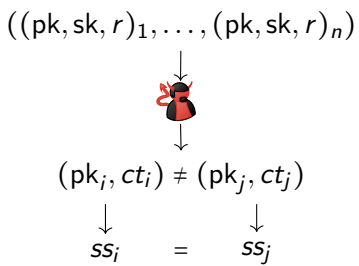

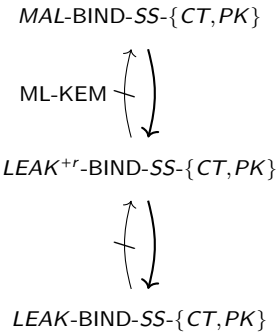

Signal: Kyber ✓
ML-KEM ✓

- related notion: SH-CR [BJKS24] is incomparable

Concrete Hybrid Bound for PQXDH against classical adversaries

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

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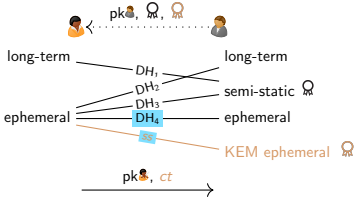

Concrete Bound for PQXDH Against Active-Later-Quantum Adversaries

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

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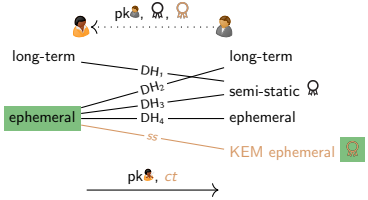

Concrete Bound for PQXDH Against Quantum Adversaries

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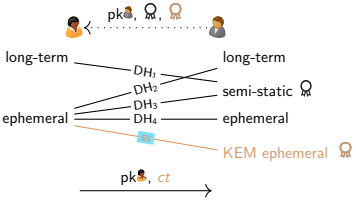
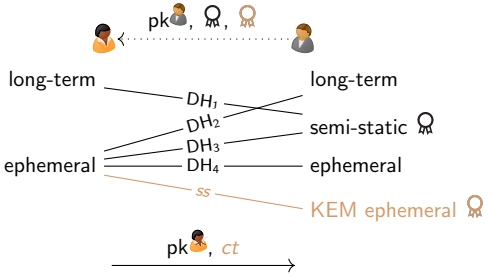


Design Discussion of PQXDH

- adding KEM *ss* to the KDF input achieves hybrid security
- secure against active-now-quantum-later due to signature on ephemeral KEM key
- should add context to KDF (especially KEM pk, ct) [BJKS24]
  - forgo binding assumption on KEM
  - tighter proof
- needed: domain separation on signatures against key confusion attacks
  - DH vs KEM [BJKS24]
  - ephemeral vs semi-static KEM

PQXDH Provides Hybrid Key Indistinguishability



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

$$+ (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_p \cdot n_{ss} \cdot \epsilon_{\mathsf{GDH}})) \quad // \ \mathsf{clean}_{\mathsf{LT\text{-}SS}}$$
$$+ (n_s \cdot n_p \cdot \epsilon_{\mathsf{GDH}}) \quad // \ \mathsf{clean}_{\mathsf{E\text{-}LT}}$$
$$+ (n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \epsilon_{\mathsf{GDH}})) \quad // \ \mathsf{clean}_{\mathsf{E\text{-}SS}} \wedge \mathsf{type} = \mathsf{full}$$
$$+ \left(n_p \cdot (\epsilon_{\mathsf{SIG}} + n_{ss} \cdot n_s \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon^{\mathsf{OW}}_{\mathsf{CCA}}))\right) \quad // \ \mathsf{clean}_{\mathsf{E\text{-}SS}} \wedge \mathsf{type} = \mathsf{reduced}$$
$$+ \left(n_s^2 \cdot \min(\epsilon_{\mathsf{GDH}}, \epsilon^{\mathsf{OW}}_{\mathsf{CCA}})\right) \quad // \ \mathsf{clean}_{\mathsf{E\text{-}E}} \wedge \mathsf{clean}_{\mathsf{peerE}}$$
$$+ \left(n_p \cdot (\epsilon_{\mathsf{SIG}} + n_s^2 \cdot q_{\mathsf{RO}} \cdot \epsilon^{\mathsf{OW}}_{\mathsf{CCA}})\right) \quad // \ \mathsf{clean}_{\mathsf{E\text{-}E}} \wedge \mathsf{clean}_{\mathsf{sigE}}$$

MAL-BIND-*SS*-{*CT*,*PK*}

ML-KEM

LEAK^{+r}-BIND-*SS*-{*CT*,*PK*}

LEAK-BIND-*SS*-{*CT*,*PK*}

Signal: Kyber ✓
ML-KEM ✓

or include the session context in key derivation

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

$$+ n_{ss} \cdot n_s \cdot (\epsilon^{\mathsf{IND}}_{\mathsf{FCCA}} + \epsilon_{\mathsf{PRF}}) \quad // \ \mathsf{clean}^{Q}_{\mathsf{E\text{-}SS}}$$
$$+ n_s^2 \cdot (\epsilon^{\mathsf{IND}}_{\mathsf{CCA}} + \epsilon_{\mathsf{PRF}}), \quad // \ \mathsf{clean}^{Q}_{\mathsf{E\text{-}E}}$$

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Icon References

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- (KEM) secret key icon by Yannick Lung
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different key lifetimes

long-term

long-term (use forever)

semi-static (use for a week)

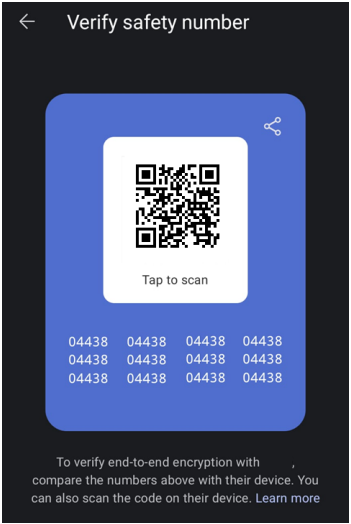
ephemeral

ephemeral (use once)

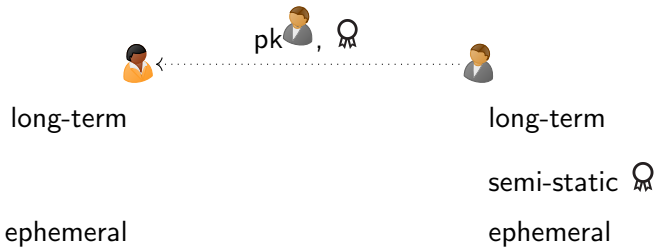
different key lifetimes

long-term	long-term (use forever)
	semi-static (use for a week)
ephemeral	ephemeral (use once)

- authenticate long-term public keys via safety number (hash of both long-term public keys)

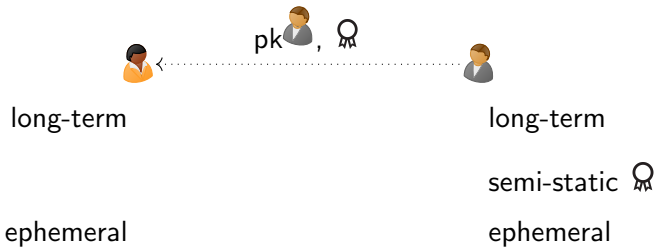


pre-key bundle



- Bob uploads semi-static key, signature, and ephemeral keys to key server

pre-key bundle



- Bob uploads semi-static key, signature, and ephemeral keys to key server
- all key pairs are DH
- long-term keys additionally for a signature scheme