Post-quantum Asynchronous Deniable Key Exchange and the Signal Handshake

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PKC 2022

Instant Messaging

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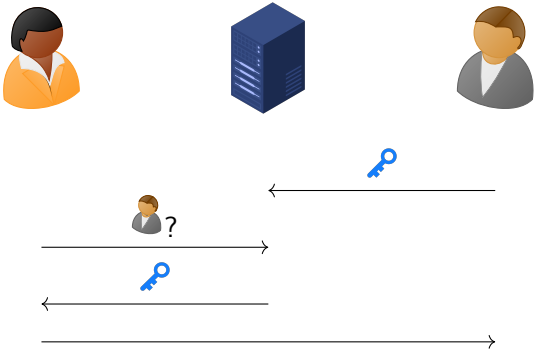
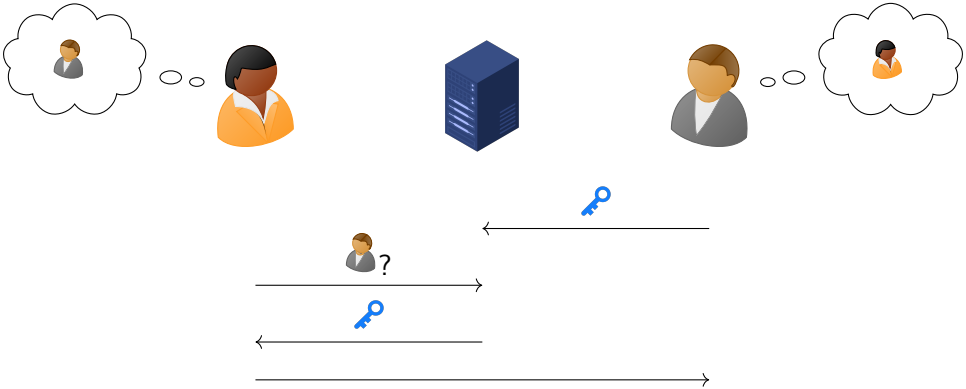


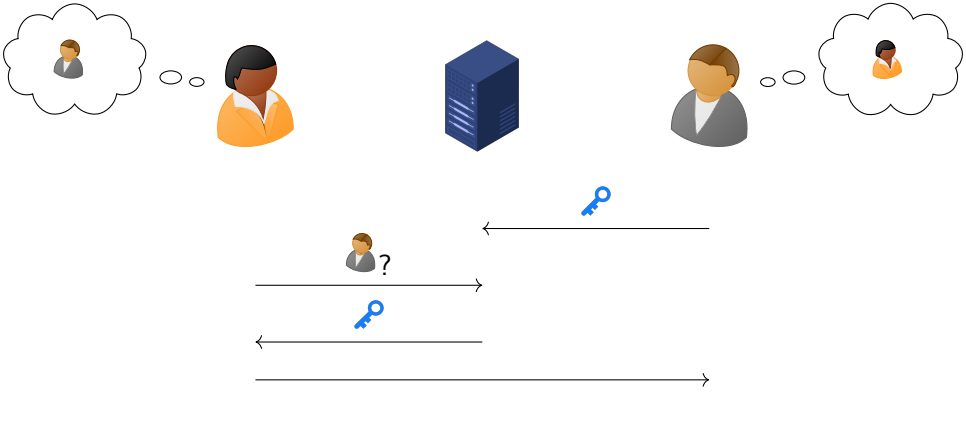
- Asynchronicity

Instant Messaging



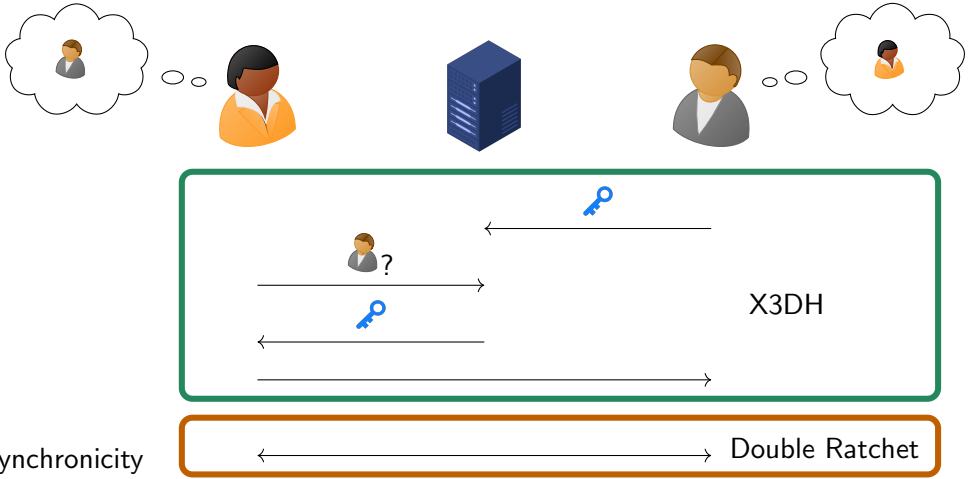
- Asynchronicity
- Mutual authentication

Instant Messaging



- Asynchronicity
- Mutual authentication
- Offline deniability **Signal**

Instant Messaging



- Asynchronicity
- Mutual authentication
- Offline deniability **Signal**

Signal initial handshake: X3DH

pre-key bundle

long-term

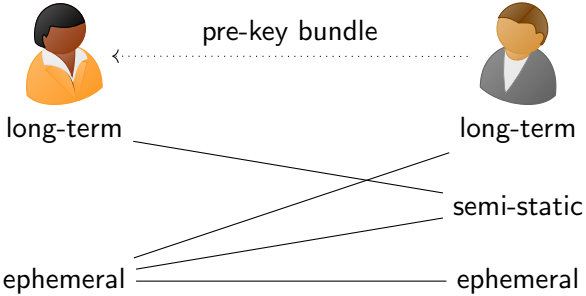
long-term

semi-static

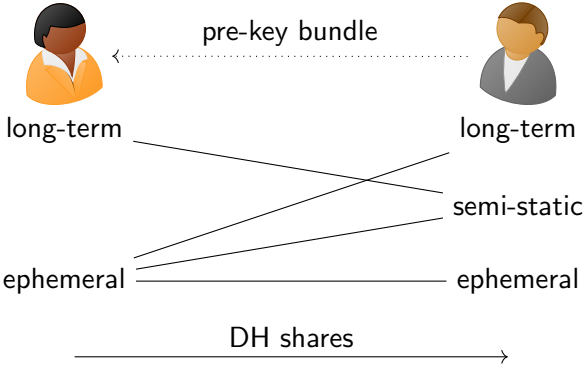
ephemeral

ephemeral

Signal initial handshake: X3DH



Signal initial handshake: X3DH



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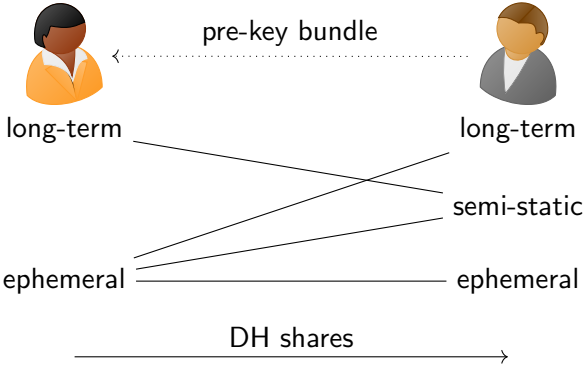

- ⚠ *not* post-quantum

Signal

Initial Handshake: X3DH

⚠ not post-quantum

Double Ratchet

post-quantum from e.g. Key Encapsulation [ACD19]

[ACD19] Alwen, Coretti, Dodis, EUROCRYPT 2019, `https://ia.cr/2018/1037`

Signal

Initial Handshake: X3DH

⚠ not post-quantum

Double Ratchet

post-quantum from e.g. Key Encapsulation [ACD19]

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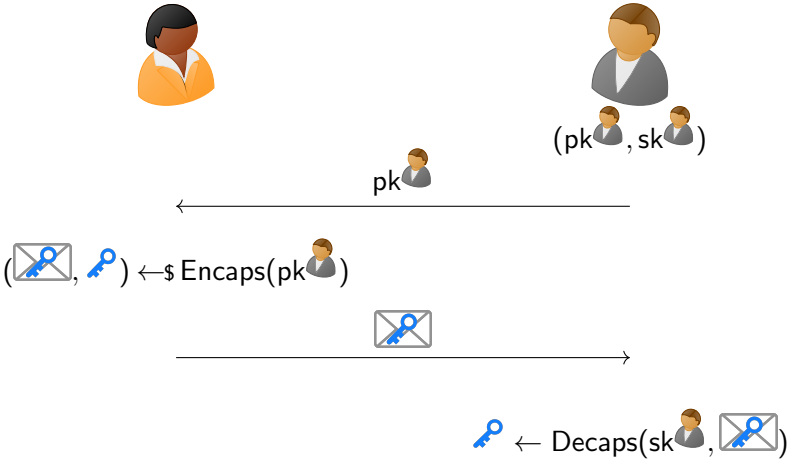
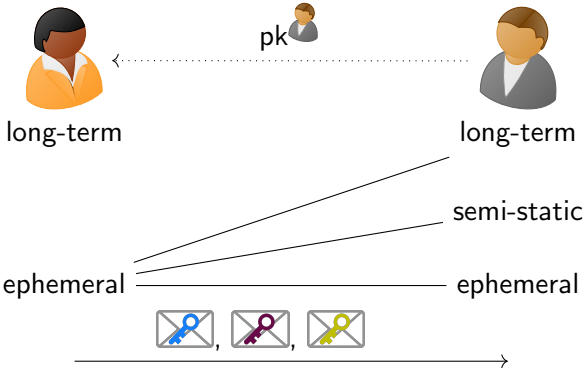
Key Encapsulation Mechanisms (KEMs)



PQSignal from KEMs?



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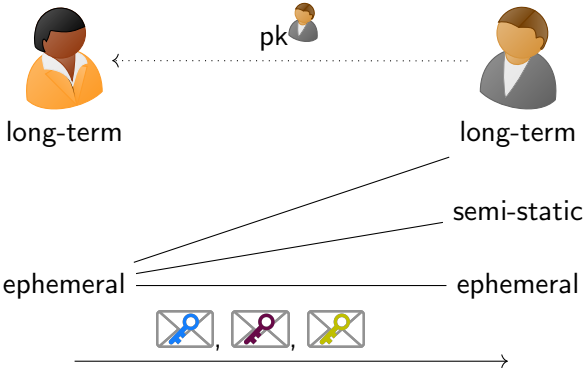

⚠ Alice-to-Bob authentication

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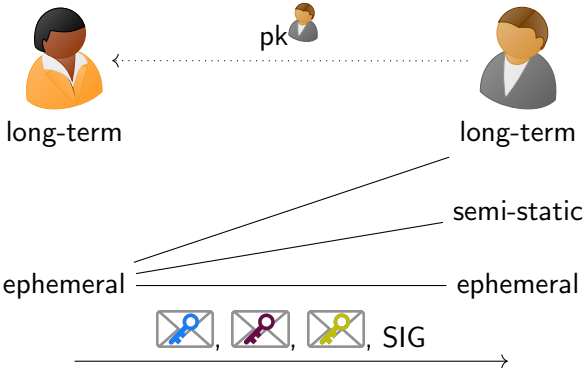

⚠ Alice-to-Bob authentication

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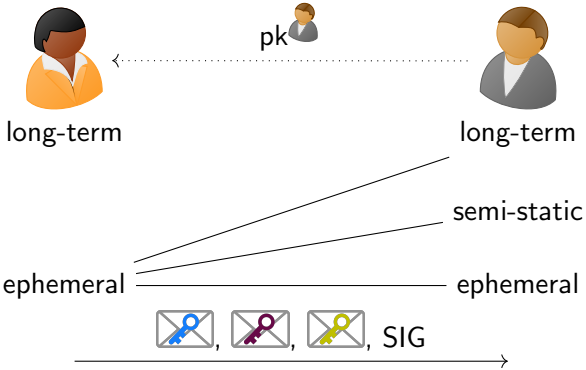


⚠ Alice-to-Bob authentication

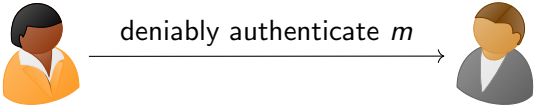
⚠ SIG breaks deniability for Alice

KEMs for PQSignal

- [BFG+20] proposed initial handshake with *split KEMs* but not instantiable
- Design idea: KEMs + deniable authentication
  - Designated Verifier Signatures **[this work]**
  - Ring Signatures [HKKP21]

[BFG+20] Brendel, Fischlin, Günther, Janson, Stebila, SAC 2020, `https://ia.cr/2019/1356`
[HKKP21] Hashimoto, Katsumata, Kwiatkowski, Prest, PKC 2021, `https://ia.cr/2021/616`

Deniable Authentication: Designated Verifier Signatures (DVS)



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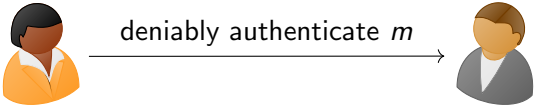

- $\mathsf{Sign}\left(\mathsf{sk}, \mathsf{pk}, m\right) \to$ 

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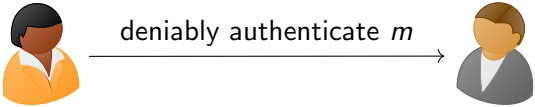
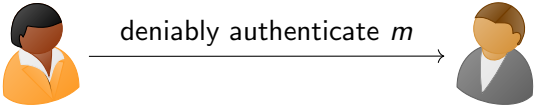


- Sign $\left(\mathsf{sk}, \mathsf{pk}, m\right) \rightarrow$
- Sim $\left(\mathsf{pk}, \mathsf{sk}, m\right) \rightarrow$

Deniable Authentication: Designated Verifier Signatures (DVS)



- Sign $\left(\mathsf{sk}, \mathsf{pk}, m\right) \to$
- Sim $\left(\mathsf{pk}, \mathsf{sk}, m\right) \to$
- source hiding: $\approx$

Post-Quantum DVS

- Direct constructions in need of more scrutiny [LLY18, ZLTT15]

[LLY18] Li, Liu, Yang, ICEBE 2018, https://doi.org/10.1109/ICEBE.2018.00062
[ZLTT15] Zhang, Liu, Tang, Tian, IJHPCN 2019, https://doi.org/10.1504/IJHPCN.2015.070013

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[this work]

2-user ring signature $\Rightarrow$ DVS

- More literature on post-quantum ring signature than DVS

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Post-Quantum DVS

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$$\begin{array}{ccc} & [\textbf{this work}] & \\ & \Rightarrow & \\ \text{2-user ring signature} & & \text{DVS} \\ & \Leftarrow & \\ & [\text{HKKP21}] & \end{array}$$

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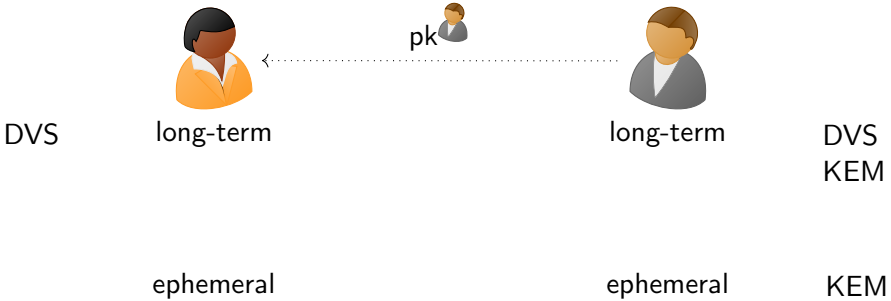
Core idea of our asynchronous DAKE protocol and [HKKP21]



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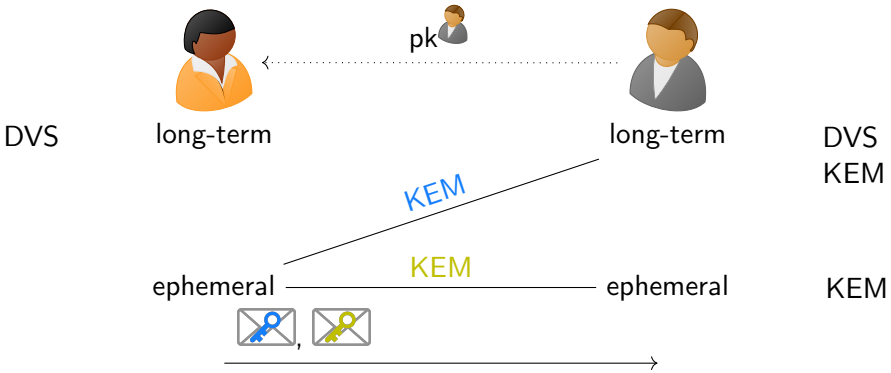

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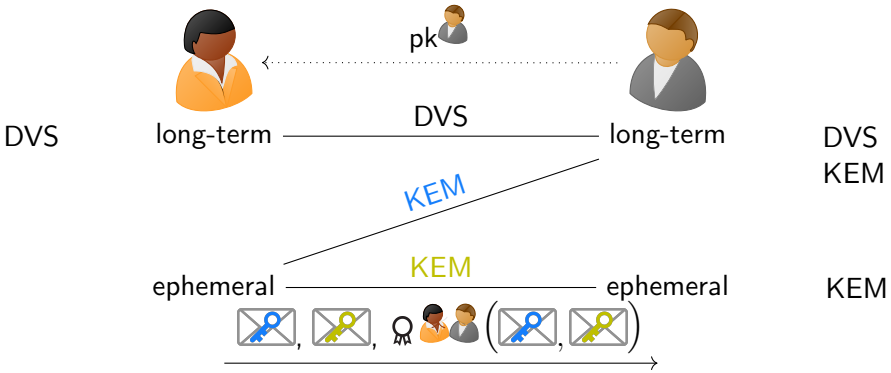

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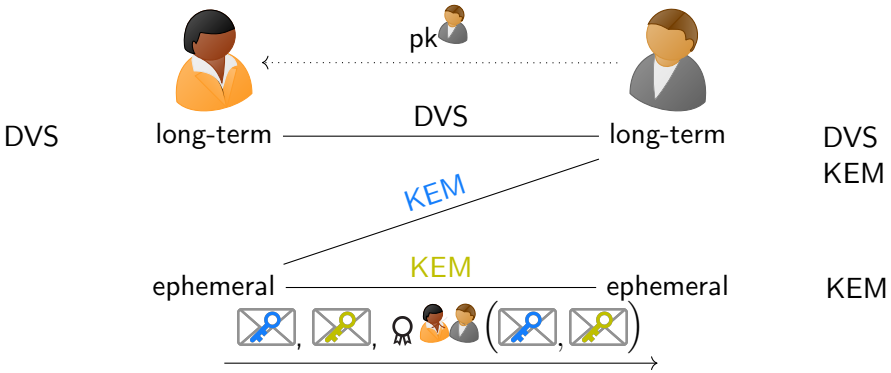

- [HKKP21] uses ring signatures instead of DVS

What is Deniability for Asynchronous DAKE?

X3DH doesn't give either Alice or Bob a publishable cryptographic proof of the contents of their communication or the fact that they communicated.
A third party that has compromised legitimate private keys from Alice or Bob could be provided a communication transcript that appears to be between Alice and Bob and that can only have been created by some other party that also has access to legitimate private keys from Alice or Bob. [MP16]

[MP16] Marlinspike, Perrin, Signal specification, `https://signal.org/docs/specifications/x3dh/`

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$\Downarrow$

(transcript, session key)

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Run(sk )

$\Downarrow$

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Fake(sk )

$\Downarrow$

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Run(sk ) Fake(sk )

$\Downarrow$ $\Downarrow$

(transcript, session key) $\approx$ (transcript', session key')

all secret keys

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Variants of Deniability

Run(sk ) Fake(sk )

$\Downarrow$ $\Downarrow$

(transcript, session key) $\approx$ (transcript', session key')

all secret keys

- Does Fake get sk  ?
- Does  get all secret keys?
- Does the judge interact during the protocol execution?

Difference to Prior Deniability Definition [DGK06]

- Our Fake requires sk 

[DGK06] Di Raimondo, Gennaro, Krawczyk, CCS 2006, `https://ia.cr/2006/280`

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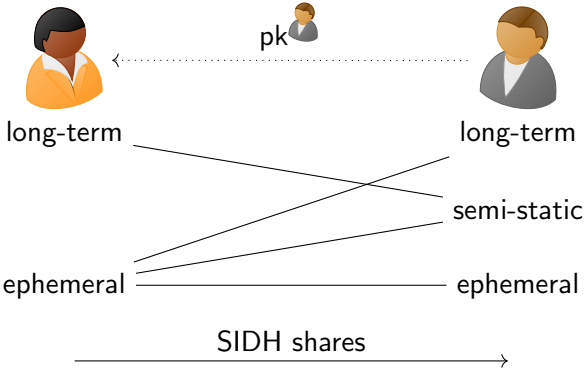
Difference to Prior Deniability Definition [DGK06]

- Our Fake requires sk 
- Our  gets all secret keys
- Proofs for their definition require knowledge assumptions

[DGK06] Di Raimondo, Gennaro, Krawczyk, CCS 2006, `https://ia.cr/2006/280`

Concurrent work: [DG21]



- Adapts DH to supsersingular isogenies ⇒ SI-X3DH
- Asynchronous, mutual authentication, offline deniability, post-quantum

[DG21] Dobson, Galbraith, ePrint, `https://ia.cr/2021/1187`

Our full construction: SPQR

- Signal in a Post-Quantum Regime (SPQR)
- Includes semi-static keys
- Security against randomness exposure via twisted PRF
- Security model analogous to original Signal analysis [CCD+17] & deniability

$\mathsf{KGenLT}()$:
$(pk^{\mathsf{KEM}}, sk^{\mathsf{KEM}}) \leftarrow\$ \mathsf{KEM}_1.\mathsf{KGen}()$
$(pk^{\mathsf{DVS}}, sk^{\mathsf{DVS}}) \leftarrow\$ \mathsf{DVS}.\mathsf{SKGen}()$
$tk \leftarrow \mathsf{tPRF}.\mathsf{KGen}()$
$pk \leftarrow (pk^{\mathsf{KEM}}, pk^{\mathsf{DVS}})$
$sk \leftarrow (sk^{\mathsf{KEM}}, sk^{\mathsf{DVS}}, tk)$
return (pk, sk)

$\mathsf{KGenSS}()$:
$(sspk^{\mathsf{KEM}}, sssk^{\mathsf{KEM}}) \leftarrow\$ \mathsf{KEM}_2.\mathsf{KGen}()$
$(sspk^{\mathsf{DVS}}, sssk^{\mathsf{DVS}}) \leftarrow\$ \mathsf{DVS}.\mathsf{VKGen}()$
$sspk \leftarrow (sspk^{\mathsf{KEM}}, sspk^{\mathsf{DVS}})$
$sssk \leftarrow (sssk^{\mathsf{KEM}}, sssk^{\mathsf{DVS}})$
return $(sspk, sssk)$

$\mathsf{KGenEP}()$:
return $(epk, esk) \leftarrow\$ \mathsf{KEM}_3.\mathsf{KGen}()$

Alice | **Signal Server** | **Bob**

Initiator Registration
$(pk_A, sk_A) \leftarrow\$ \mathsf{KGenLT}()$

Responder Registration
$(\mathsf{pk}_B, sk_B) \leftarrow\$ \mathsf{KGenLT}()$
$(sspk_B, sssk_B) \leftarrow\$ \mathsf{KGenSS}()$

Responder Ephemeral Key Generation
$(epk_B, esk_B) \leftarrow\$ \mathsf{KGenEP}()$

Send Pre-Key Bundle to Initiator

$B, pk_B, sspk_B, epk_B$ ⇠

define: $cid := (B, \mathsf{pk}_B, sspk_B, epk_B)$

define: $sid := (A, B, pk_A, pk_B, sspk_B, epk_B, n, c_1, c_2, c_3)$

Initiator Key Agreement and Protocol Message

$(sk_A^{\mathsf{KEM}}, sk_A^{\mathsf{DVS}}, tk_A) \leftarrow sk_A$

$(pk_B^{\mathsf{KEM}}, pk_B^{\mathsf{DVS}}) \leftarrow pk_B$
$(sspk_B^{\mathsf{KEM}}, sspk_B^{\mathsf{DVS}}) \leftarrow sspk_B$
$(n, r) \leftarrow\$ \{0,1\}^\lambda \times \mathcal{R}_{\mathsf{HHF}}$
$r_1 || r_2 || r_3 || r_4 \leftarrow \mathsf{tPRF}(tk_A, r)$
$(K_1, c_1) \leftarrow \mathsf{KEM}_1.\mathsf{Encaps}(\mathsf{pk}_B^{\mathsf{KEM}}; r_1)$
$(K_2, c_2) \leftarrow \mathsf{KEM}_1.\mathsf{Encaps}(sspk_B^{\mathsf{KEM}}; r_2)$
if $epk_B \neq \perp$
$\quad (K_3, c_3) \leftarrow \mathsf{KEM}_3.\mathsf{Encaps}(epk_B; r_3)$
else $(K_3, c_3) \leftarrow (\varepsilon, \varepsilon)$
$\mathsf{ms} \leftarrow K_1 || K_2 || K_3$
$\sigma \leftarrow \mathsf{DVS.Sign}(sk_A^{\mathsf{DVS}}, sspk_B^{\mathsf{DVS}}, sid; r_4)$
$K \leftarrow \mathsf{KDF}(\mathsf{ms}, sid)$
$m \leftarrow (A, pk_A, n, c_1, c_2, c_3, \sigma)$
return $(K, sid, \mathsf{accepted}, m)$

Responder Key Agreement (on input m)

$(sk_B^{\mathsf{KEM}}, sk_B^{\mathsf{DVS}}, tk_B) \leftarrow sk_B$
$(sssk_B^{\mathsf{KEM}}, sssk_B^{\mathsf{DVS}}) \leftarrow sssk_B$
$(\mathsf{pk}_A^{\mathsf{KEM}}, pk_A^{\mathsf{DVS}}) \leftarrow pk_A$
$(sspk_A^{\mathsf{KEM}}, sspk_A^{\mathsf{DVS}}) \leftarrow sspk_B$
if $\mathsf{DVS.Vrfy}(\mathsf{pk}_A^{\mathsf{DVS}}, sspk_B^{\mathsf{DVS}}, sid, \sigma) = \mathsf{false}$
$\quad$ **return** $(\perp, \perp, \mathsf{rejected}, \perp)$
$K_1 \leftarrow \mathsf{KEM}_1.\mathsf{Decaps}(sk_B^{\mathsf{KEM}}, c_1)$
$K_2 \leftarrow \mathsf{KEM}_2.\mathsf{Decaps}(sssk_B^{\mathsf{KEM}}, c_2)$
if $esk_B \neq \perp$
$\quad K_3 \leftarrow \mathsf{KEM}_3.\mathsf{Decaps}(esk_B, c_3)$
else $(K_3, c_3) \leftarrow (\varepsilon, \varepsilon)$
$\mathsf{ms} \leftarrow K_1 || K_2 || K_3$
$K \leftarrow \mathsf{KDF}(\mathsf{ms}, sid)$
return $(K, sid, \mathsf{accepted}, \varepsilon)$

$m = (A, pk_A, n, c_1, c_2, c_3, \sigma)$ ⇢

Responder Fake transcript
run *Responder Ephemeral Key Generation*, and *Initiator Key Agreement* with a modified randomness sampling and DVS generation:
$(K_1, c_1) \leftarrow\$ \mathsf{KEM}_1.\mathsf{Encaps}(\mathsf{pk}_B^{\mathsf{KEM}})$
$(K_2, c_2) \leftarrow\$ \mathsf{KEM}_2.\mathsf{Encaps}(sspk_B^{\mathsf{KEM}})$
if $epk_B \neq \perp$ $\quad (K_3, c_3) \leftarrow\$ \mathsf{KEM}_3.\mathsf{Encaps}(epk_B)$
else $\quad (K_3, c_3) \leftarrow (\varepsilon, \varepsilon)$
$\sigma \leftarrow\$ \mathsf{DVS.Sim}(sssk_B^{\mathsf{DVS}}, \mathsf{pk}_A^{\mathsf{DVS}}, sid)$
$K \leftarrow \mathsf{KDF}(\mathsf{ms}, sid)$
return $(K, m = (B, pk_B, sspk_B, epk_B, A, pk_A, n, c_1, c_2, c_3, \sigma))$

[CCD+17] Cohn-Gordon, Cremers, Dowling, Garratt, Stebila, EuroS&P, https://ia.cr/2016/1013

Comparison of initial handshake protocols

			deniability		
		PQ	strong judge	[DGK06]	full scope
X3DH	DH	✗	•	✓ [VGIK20]	✓
SC-DAKE [HKKP21]	KEM + RingSIG	✓	•	✗	✗
SC-DAKE′ [HKKP21]	+ NIZK	✓	•	✓	✗
SPQR [this work]	KEM + DVS	✓	✓	✗	✓
SI-X3DH [DG21]	SIDH	✓	•	✓	✓

✓ proven ✗ broken • conjectured to hold

full scope: real-world setting including semi-static keys

[VGIK20] Vatandas, Gennaro, Ithurburn, Krawczyk, ACNS 2020, `https://ia.cr/2020/642`

Signal goes post-quantum?

Initial Handshake

post-quantum from Key Encapsulation and Designated Verifier Signatures

deniability against strong judges

DVS from ring signatures

Double Ratchet

post-quantum from e.g. Key Encapsulation [ACD19]

Full paper: `https://eprint.iacr.org/2021/769`

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Picture references

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