XHMQV: Better Efficiency and Stronger Security for Signal's Initial Handshake based on HMQV

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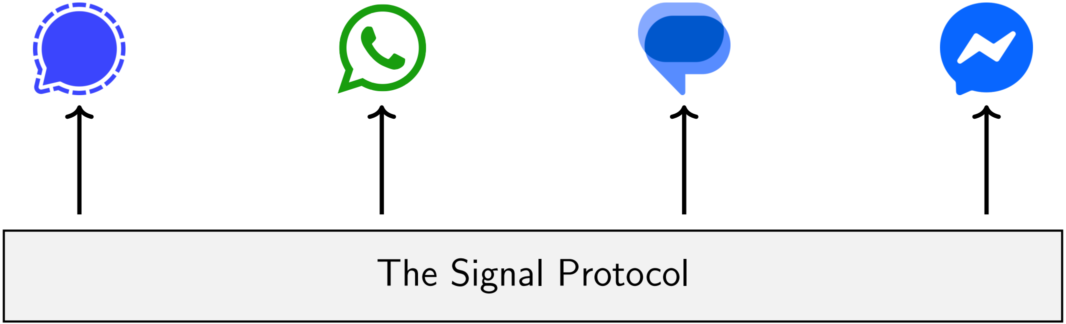
The Signal Protocol



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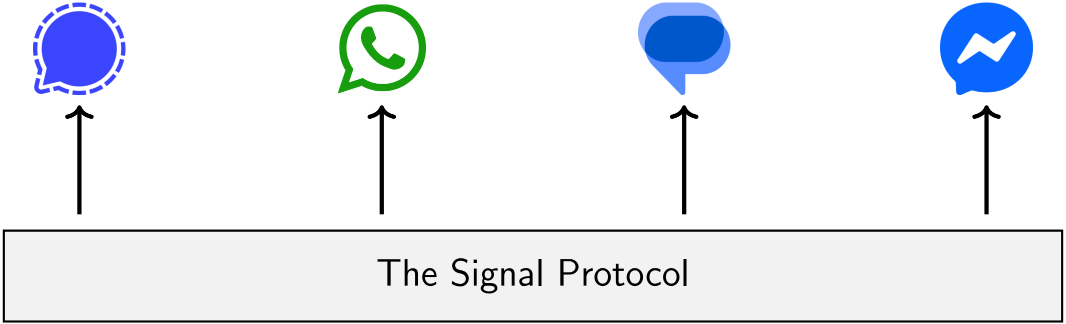


The Signal Protocol

Secure messaging – A very active area in the academic community

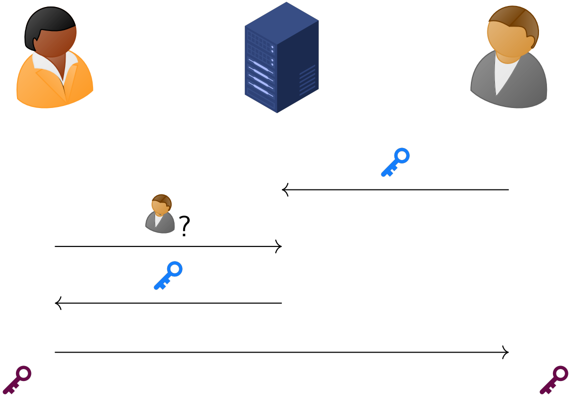
- Formal security analysis, e.g., [CCD$^+$20, CRT24]
- Extension to group messaging, e.g., [CCG$^+$18]
- Post-quantum extension (PQXDH), e.g., [BFG$^+$22, FG25]
- …

Our Contributions

- XHMQV: A new initial handshake protocol that is
  - More efficient
  - Stronger “maximum-exposure” security, and
  - Proven in a more realistic security way (namely, being able to handle the key reuse issue)

  than X3DH (aka. Signal’s classical initial handshake).

Signal: Asynchronous Authenticated Key Exchange



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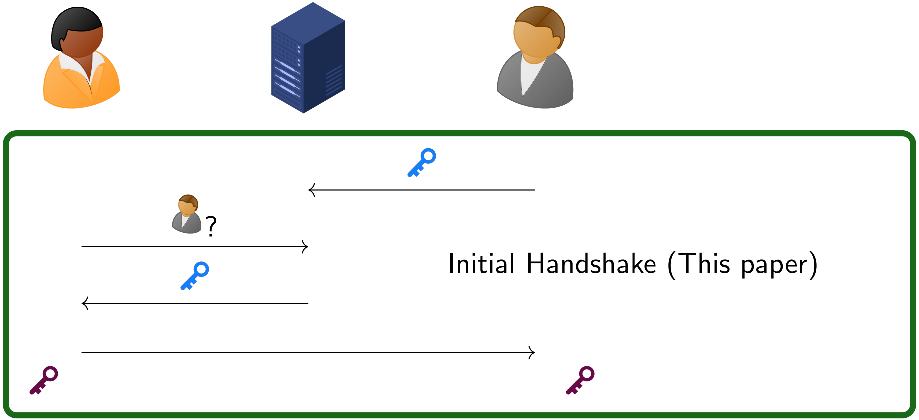

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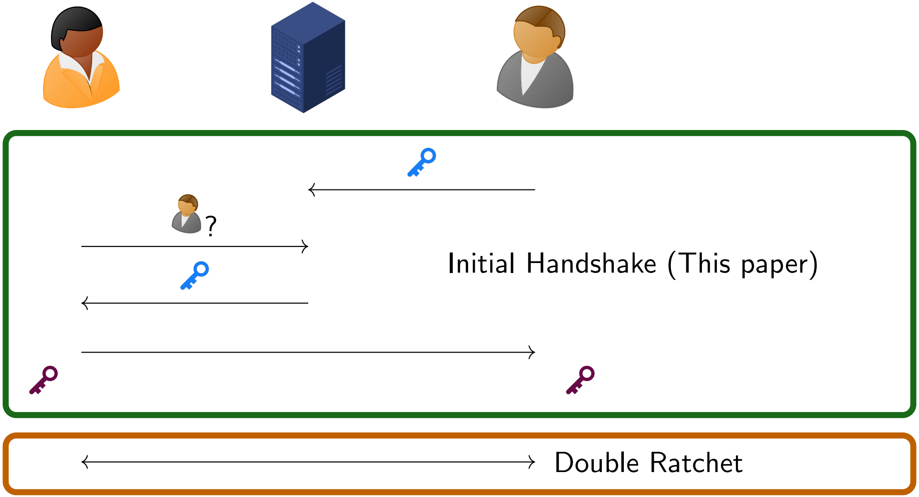

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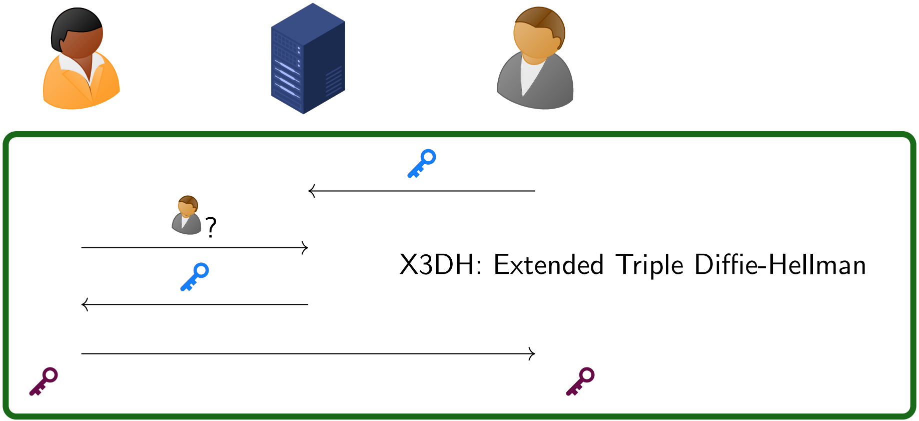

X3DH: Extended Triple Diffie-Hellman

X3DH: Signal's Initial Handshake

long-term (a, g^a)

long-term (b, g^b)

semi-static (s, g^s)

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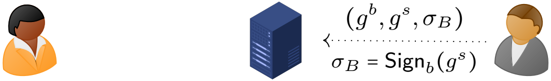

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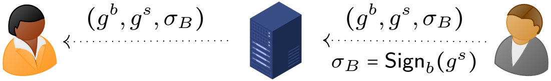

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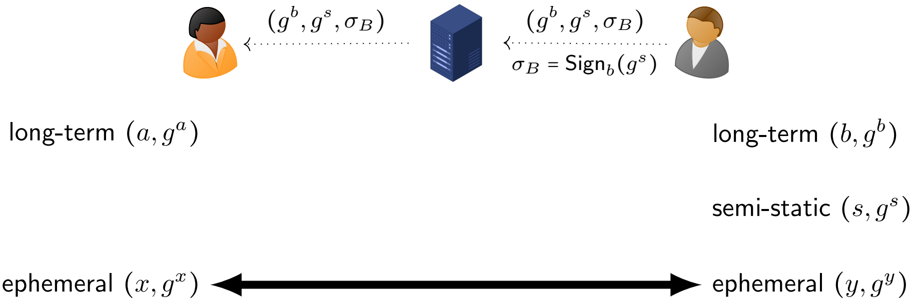

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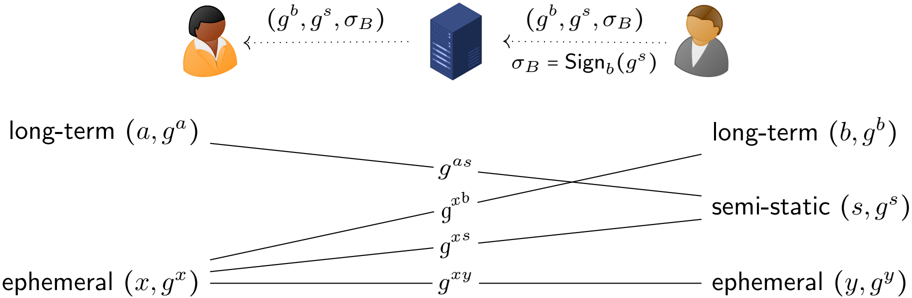

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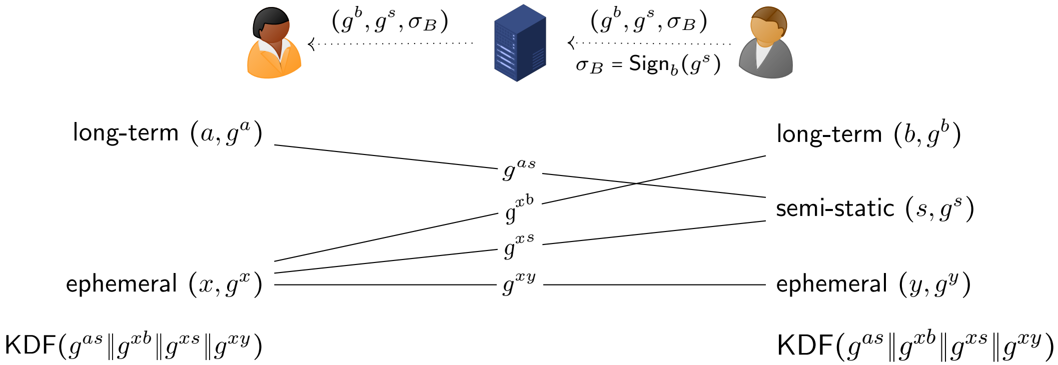

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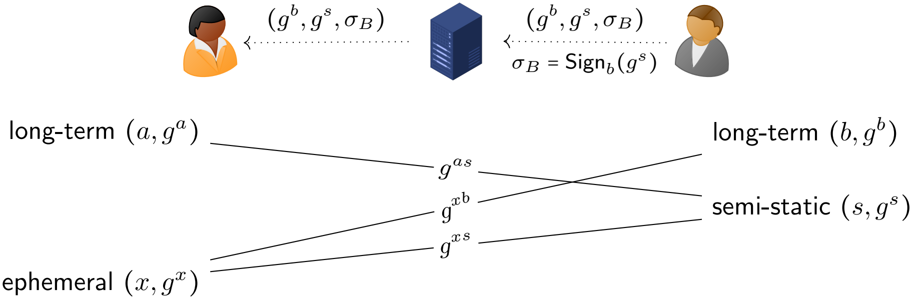

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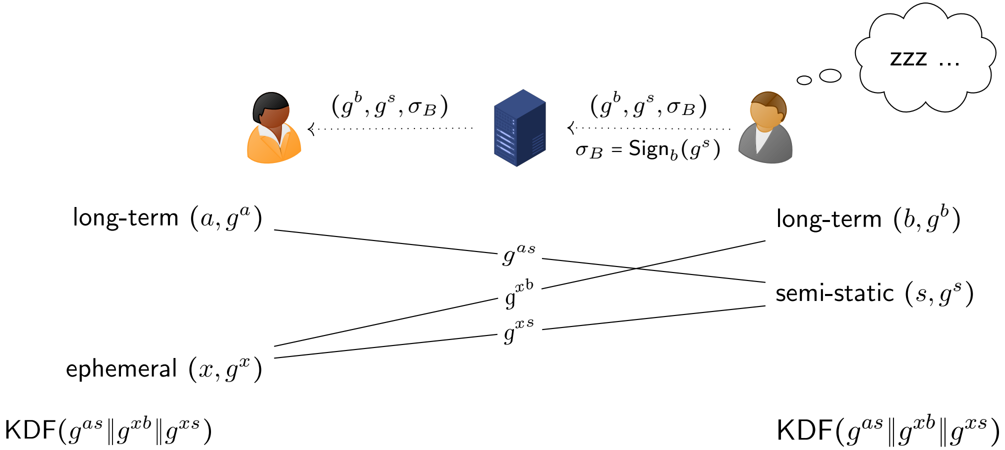

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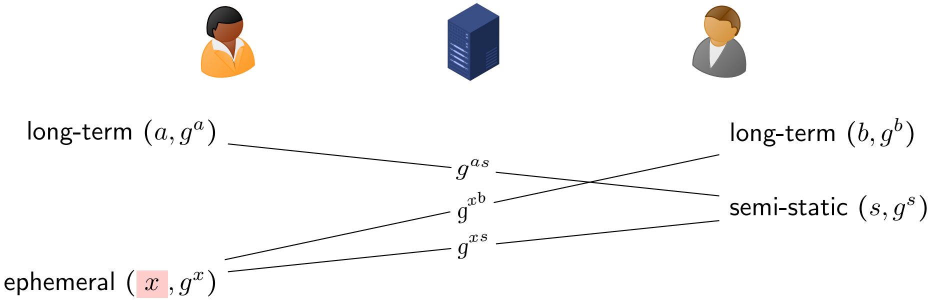

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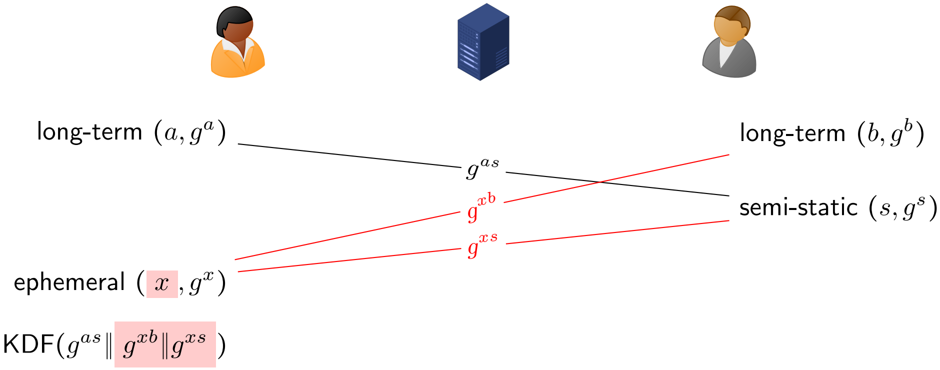

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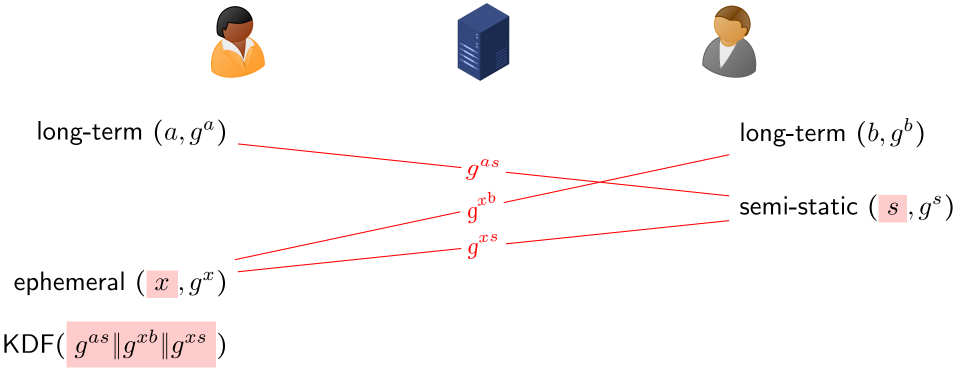

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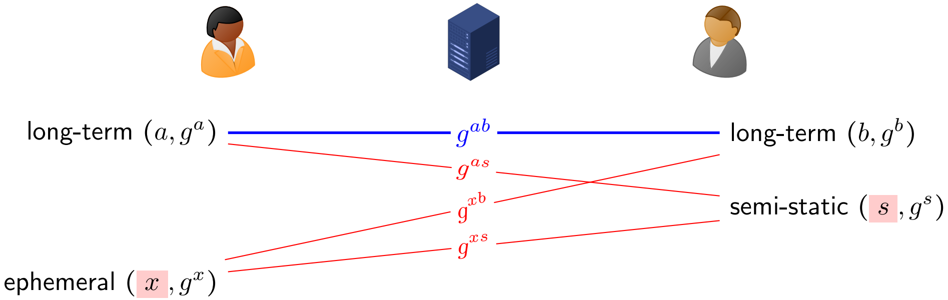
A Solution



long-term (a, g^a)

g^{ab}

long-term (b, g^b)

g^{as}

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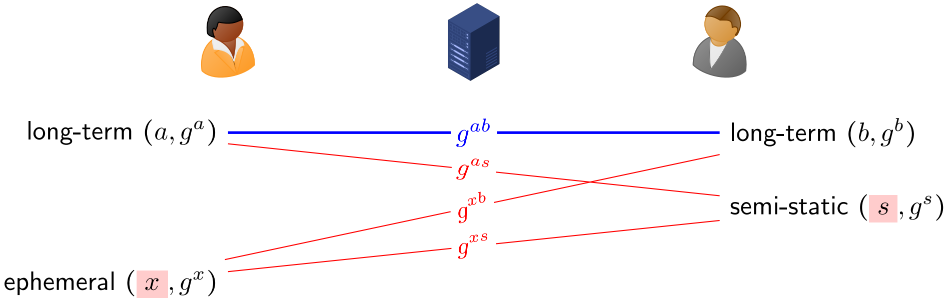

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Already *efficiently* solved by HMQV [Kra05]?

HMQV [Kra05]

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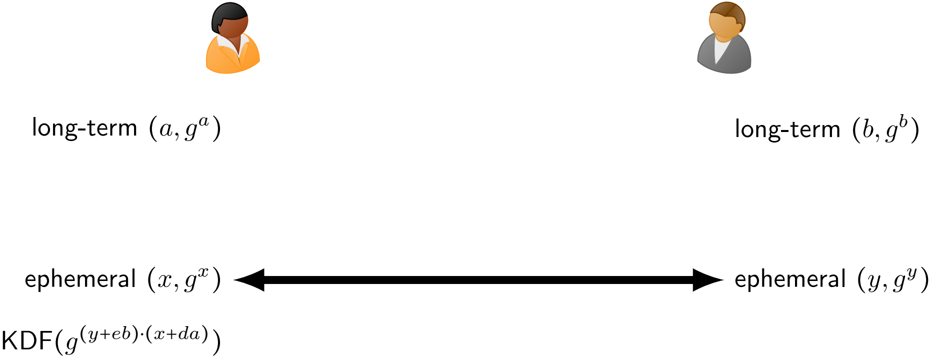
[*] $e = H(g^y \| \text{Alice})$ and $d = H(g^x \| \text{Bob})$

HMQV [Kra05]



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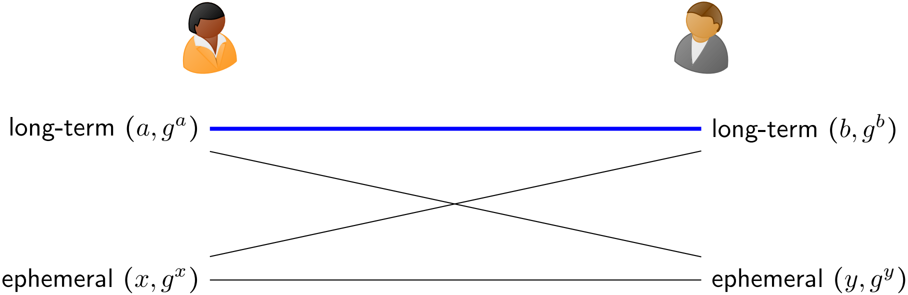

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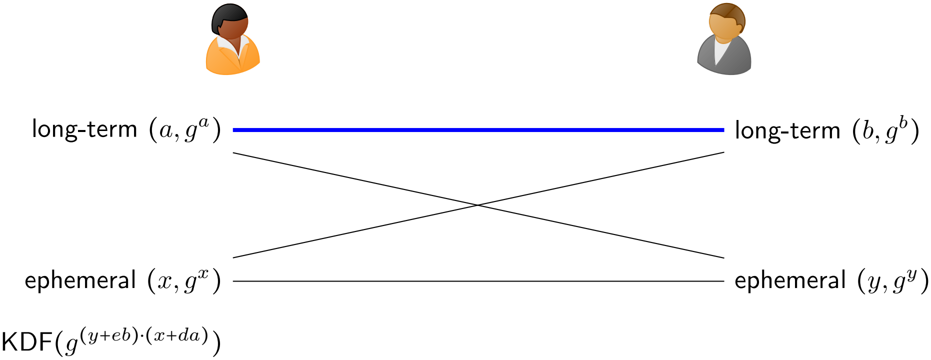

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- More efficient (#Exp $=$ 2 for HMQV and 4 for X3DH) ✓
- Stronger "maximum-exposure" security ✓
- Not asynchronous ✗

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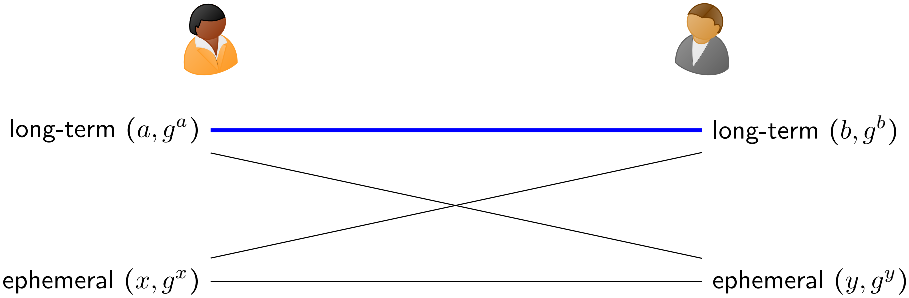

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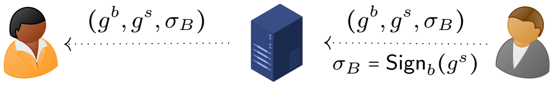
  $\Rightarrow$ Introducing a semi-static key g^s

Overview of Our XHMQV



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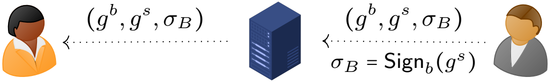

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HMQV: $\mathsf{KDF}(g^{(y+eb)\cdot(x+da)})$

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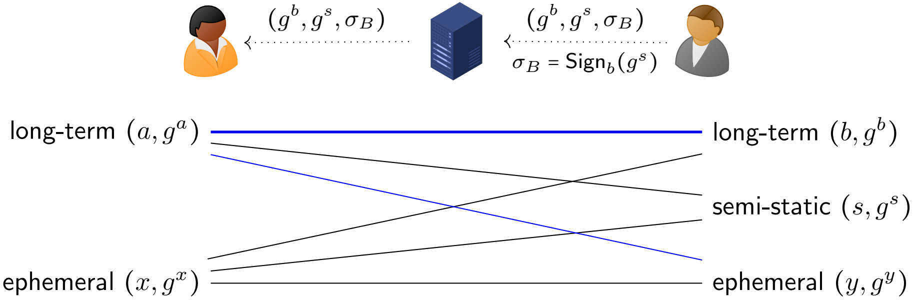

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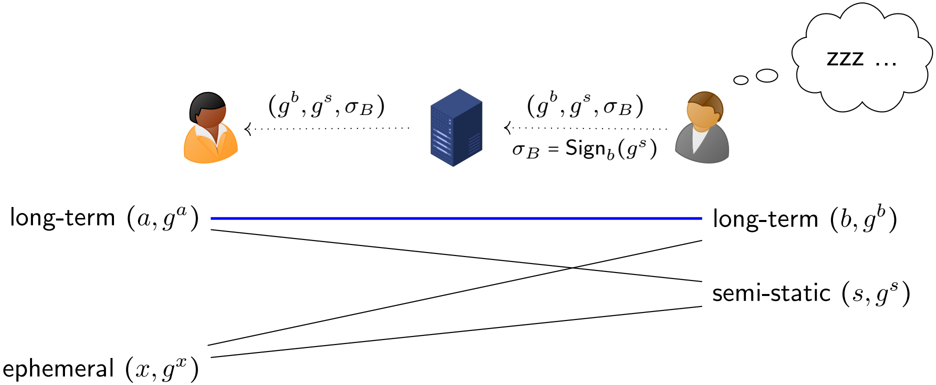

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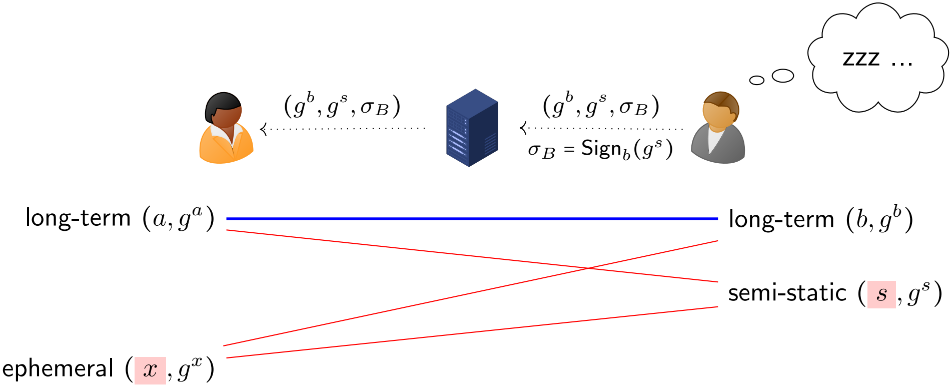

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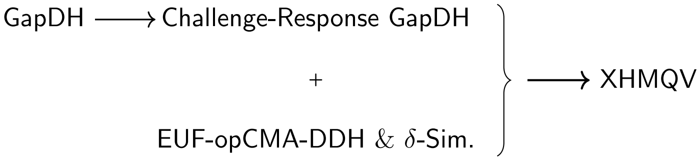
Security of XHMQV



$$\left.\begin{array}{r} \text{GapDH} \longrightarrow \text{Challenge-Response GapDH} \\ + \\ \text{EUF-opCMA-DDH} \ \& \ \delta\text{-Sim.} \end{array}\right\} \longrightarrow \text{XHMQV}$$

- Game-based Model as in [CCD+20, BFG+22, FG25]
- Random Oracles

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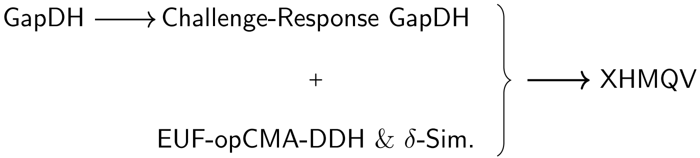
GapDH ⟶ Challenge-Response GapDH

+

EUF-opCMA-DDH & δ-Sim.

⟶ XHMQV

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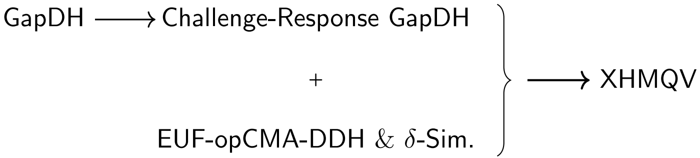
Security of XHMQV



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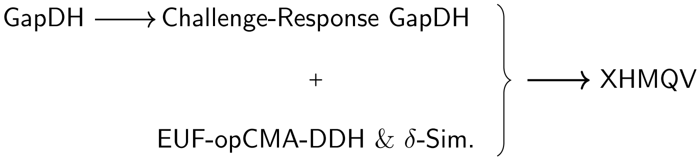
  - Handle the key reuse issue
  - Can be satisfied by (EC)DSA and Schnorr

Security of XHMQV



GapDH $\longrightarrow$ Challenge-Response GapDH

$+$

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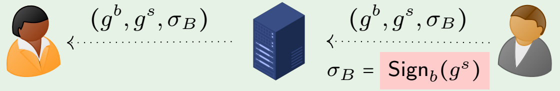
Key Reuse Issue

In the Real Protocols (X3DH, XHMQV): Signing key = long-term key



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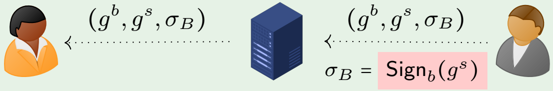

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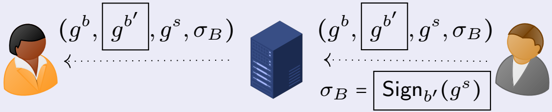
In the Proofs (e.g. [CCD+20, FG25]): Signing key ≠ long-term key



$(g^b, \boxed{g^{b'}}, g^s, \sigma_B)$

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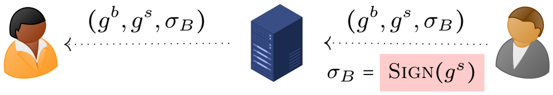
long-term (b, g^b)

signing $(\boxed{b'}, g^{b'})$

Key Reuse Issue

In the reduction to the signature security:



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long-term $(\boxed{\cancel{b}}, g^b)$

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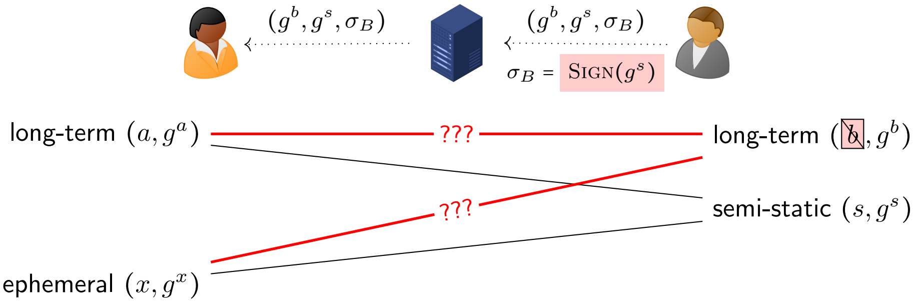

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long-term (a, g^a)

???

long-term $(\boxed{\cancel{b}}, g^b)$

???

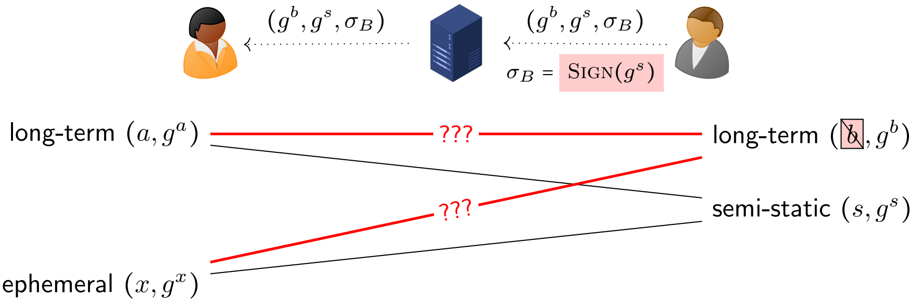
semi-static (s, g^s)

ephemeral (x, g^x)

KDF($g^{(eb+e's)\cdot(x+da)}$)=??

Key Reuse Issue

In the reduction to the signature security:



(g^b, g^s, σ_B)

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$\sigma_B = \boxed{\textsc{Sign}(g^s)}$

long-term (a, g^a)

???

long-term $(\boxed{\cancel{b}}, g^b)$

semi-static (s, g^s)

???

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Our Solution: EUF-opCMA-DDH ≈ EUF-CMA

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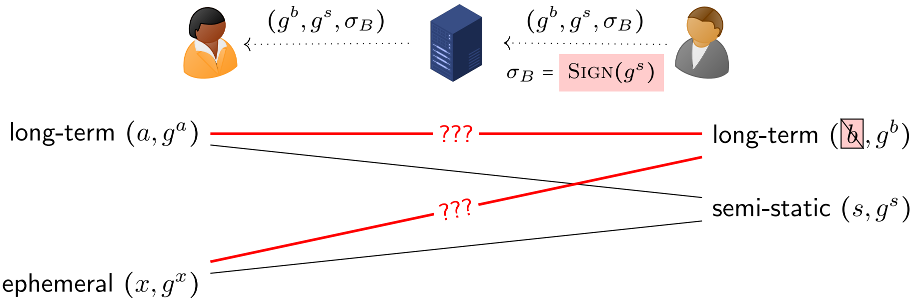

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Our Solution: EUF-opCMA-DDH ≈ EUF-CMA

- opCMA: One-per message (Weaker than EUF-CMA)
- DDH Oracle: Allows us to compute $\mathsf{KDF}(g^{(eb+e's)\cdot(x+da)})$ by programming the RO

Security and Efficiency Comparison

Schemes	#Exp	Ephemeral & semi-static leak	Other leak	Security bound	Key reuse?
X3DH	8 (6)	insecure	secure	$O(\sqrt{\varepsilon_{\mathsf{DL}}})^{\dagger}$	✗
XHMQV	5 (4)	secure	secure	$O(\sqrt{\varepsilon_{\mathsf{GapDH}}})^{\ddagger}$	✓

[†] $\sqrt{\varepsilon_{\mathsf{DL}}}$-loss is due to (EC)DSA used in X3DH, where $\varepsilon_{\mathsf{DL}}$ is the probability of breaking DL

[‡] $\sqrt{\varepsilon_{\mathsf{GapDH}}}$-loss comes from GapDH → CRGapDH (cf. [KPRR23])

Conclusion

XHMQV: An initial handshake protocol

- Asynchronous
- More efficient due to fewer exponentiation
- Stronger "maximum-exposure" security
- Similar deniability as X3DH [FL25]
- More realistic security proofs that consider key reuse

[FL25] R. Fiedler and R. Langrehr: On Deniable Authentication against Malicious Verifiers. In CRYPTO'25.

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Open Problems

- Achieving the same level of "maximum-exposure" security in the post-quantum setting?
- Extending our analysis of key reuse to other protocols?
- Achieving subversion-resilient security using reverse firewall [DMSDT25] ?

[DMSDT25] Y. Dodis, B. Magri, N. Stephens-Davidowitz, and Y. Tselekounis: Guarding the Signal: Secure Messaging with Reverse Firewalls. In CRYPTO'25.

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Icon References

- server icon by Alexiuz AS
- public key icon by Yannick Lung
- Secure messaging app icons are by Signal, WhatsApp, Google Messages, Facebook Messenger