Updatable Signatures and Message Authentication Codes

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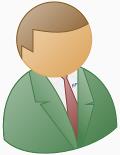
Motivation

- Rotate keys and update signatures/MACs to the new key (using a compact token),
- Previous work on Updatable Encryption (e.g., [Bon+13] and [LT18]),
- Equally important in context of signatures and MACs to follow good key management practices (e.g., key-rotation in software distribution).

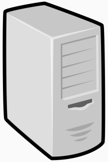
Our Framework

Definition

epoch $\boldsymbol{e}$

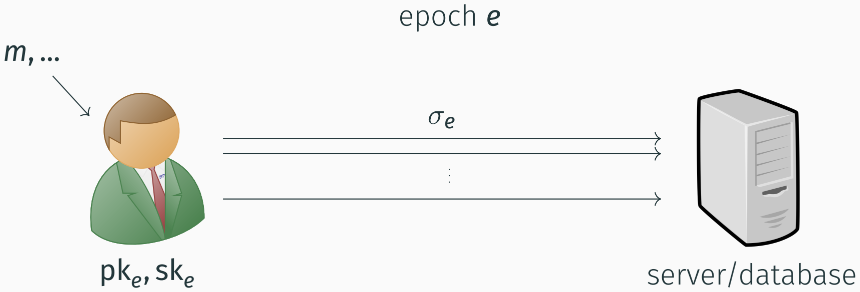


$\mathsf{pk}_e, \mathsf{sk}_e$



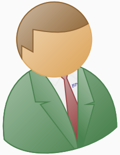
server/database

Definition


epoch e
$m, \ldots$
σ_e
$\mathsf{pk}_e, \mathsf{sk}_e$
server/database

Definition

epoch $\boldsymbol{e}$



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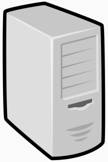
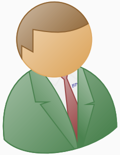


σ_e

server/database

Definition

epoch e



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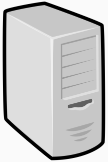
pk_e, sk_e

Next

σ_e



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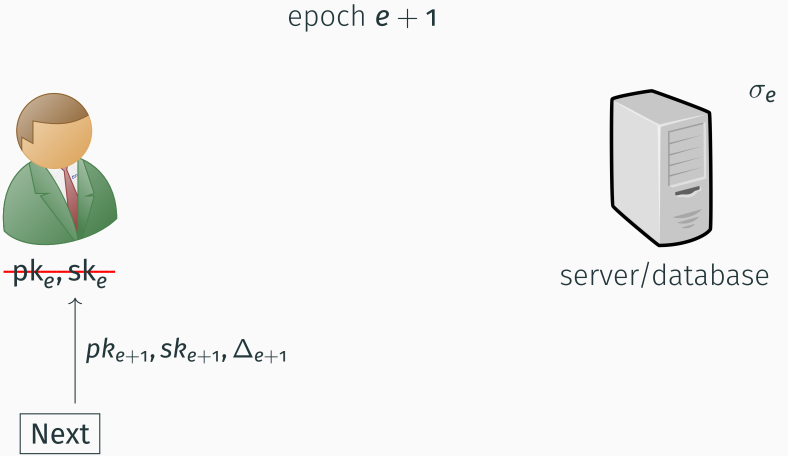
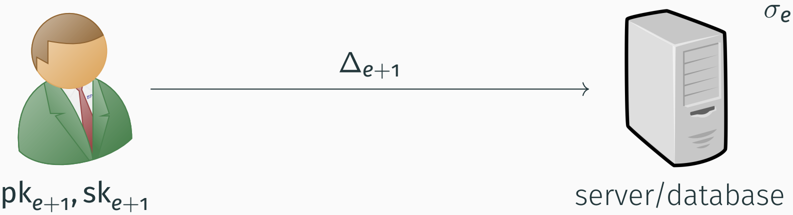

epoch $e+1$
σ_e
pk_e, sk_e
server/database
$pk_{e+1}, sk_{e+1}, \Delta_{e+1}$
Next

Definition

epoch $e + 1$



Definition

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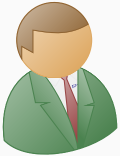

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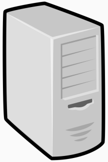

server/database

σ_e → σ_{e+1}

Update

Security

We introduced two security notions:

- existential unforgeability under chosen-message attack (UX-EUF-CMA),
- unlinkable updates under chosen-message attack (UX-UU-CMA),

for $\mathsf{X} \in \{\text{MAC}, \text{S}\}$.

Leakage Profile [LT18]

We use the concept of a leakage profile originally defined, for updatable encryption, in [LT18], to capture key, token, and signature "leakage" that cannot be directly captured via oracles.

- Key-update inferences,
- Token inferences,
- Signature-update inferences,

Example of Leakage

epoch:	$e-5$	$e-4$	$e-3$	$e-2$	$e-1$	e	$e+1$	$e+2$	$e+3$	$e+4$
keys:	k_{e-5}	**k_{e-4}**	k_{e-3}	**k_{e-2}**	k_{e-1}	k_e	**k_{e+1}**	k_{e+2}	k_{e+3}	k_{e+4}
tokens:	**Δ_{e-4}**	Δ_{e-3}	**Δ_{e-2}**	Δ_{e-1}	**Δ_e**	Δ_{e+1}	**Δ_{e+2}**	Δ_{e+3}	Δ_{e+4}	**Δ_{e+5}**
signature:	σ_{e-5}	**σ_{e-4}**	σ_{e-3}	σ_{e-2}	σ_{e-1}	σ_e	**σ_{e+1}**	σ_{e+2}	**σ_{e+3}**	σ_{e+4}

Figure 1: Example of directly obtained (green) and inferable information (blue) for UX schemes.

Example of Leakage

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keys:	k_{e-5}	k_{e-4}	k_{e-3}	k_{e-2}	k_{e-1}	k_e	k_{e+1}	k_{e+2}	k_{e+3}	k_{e+4}
tokens:	Δ_{e-4}	Δ_{e-3}	Δ_{e-2}	Δ_{e-1}	Δ_e	Δ_{e+1}	Δ_{e+2}	Δ_{e+3}	Δ_{e+4}	Δ_{e+5}
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tokens:	Δ_{e-4}	Δ_{e-3}	Δ_{e-2}	Δ_{e-1}	Δ_e	Δ_{e+1}	Δ_{e+2}	Δ_{e+3}	Δ_{e+4}	Δ_{e+5}
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tokens:	Δ_{e-4}	Δ_{e-3}	Δ_{e-2}	Δ_{e-1}	Δ_e	Δ_{e+1}	Δ_{e+2}	Δ_{e+3}	Δ_{e+4}	Δ_{e+5}
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tokens:	Δ_{e-4}	Δ_{e-3}	Δ_{e-2}	Δ_{e-1}	Δ_e	Δ_{e+1}	Δ_{e+2}	Δ_{e+3}	Δ_{e+4}	Δ_{e+5}
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Constructions

Outline

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- Security Proof Ideas.

Key-Homomorphic Signatures [DS19] (1/2)

Definition (Secret Key to Public Key Homomorphism [DS19])

Let Σ be a signature scheme, where secret and public key elements live in groups $(\mathbb{H}, +)$ and $(\mathbb{E}, \cdot)$ respectively. A Secret Key to Public Key Homomorphism is a map $\mu : \mathbb{H} \to \mathbb{E}$, such that:

- $\mu(sk + sk') = \mu(sk) \cdot \mu(sk')$ for all $sk, sk' \in \mathbb{H}$,
- $pk = \mu(sk)$ for all $(sk, pk) \leftarrow \mathsf{KeyGen}(\lambda)$.

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Example: DL setting $(\mathbb{G}, p, g)$

$$sk \leftarrow \mathbb{Z}_p, pk = g^{sk} \qquad \mu : \begin{cases} \mathbb{Z}_p \to \mathbb{G} \\ k \mapsto g^k \end{cases}$$

Definition (Key-Homomorphic Signatures [DS19])

A signature scheme is called key-homomorphic, if it provides a secret key to public key homomorphism and an additional PPT algorithm **Adapt**, such that for all $\Delta \in \mathbb{H}$ and all $(pk, sk) \leftarrow \mathsf{Gen}(\lambda)$, all messages $M \in \mathcal{M}$ and all σ with $\mathsf{Ver}(pk, M, \sigma) = 1$ and $(pk', \sigma') \leftarrow \mathsf{Adapt}(\mathsf{pk}, M, \sigma, \Delta)$, it holds that

$$\Pr[\mathsf{Ver}(pk', M, \sigma') = 1] = 1 \quad \wedge \quad pk' = \mu(\Delta) \cdot pk.$$

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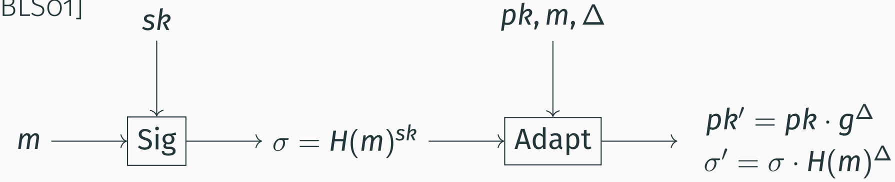
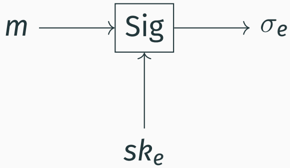
Example: [BLS01]



KH-based construction



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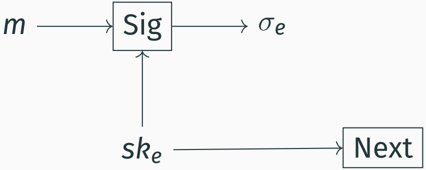

$\Delta_{e+1} \leftarrow \mathbb{H};$ $pk_{e+1} := pk_e \cdot \mu(\Delta_{e+1})$

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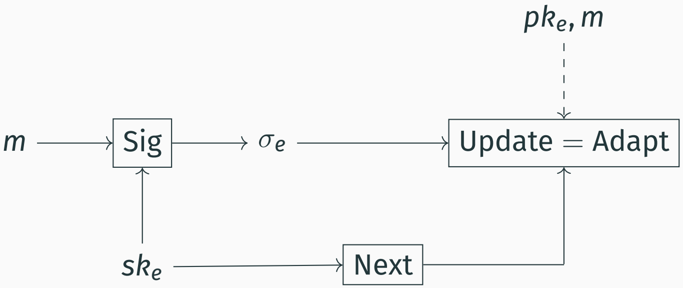

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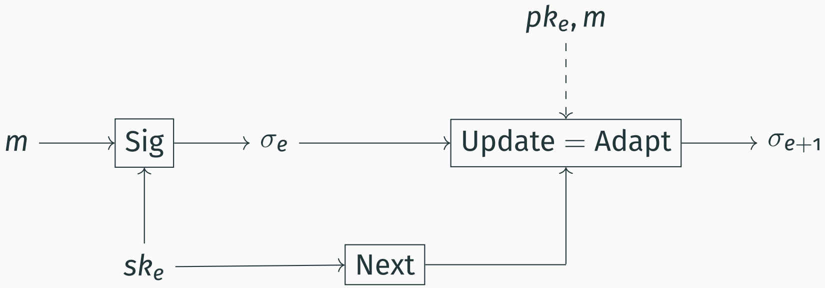

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We start from the well-known GPV signature scheme of Gentry et al. [GPV08].

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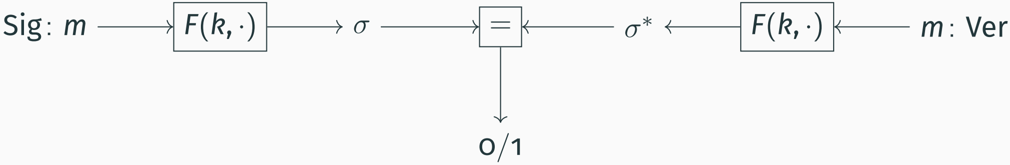

UMAC from (almost) key-homomorphic PRFs

Definition (Key-Homomorphic PRFs [Bon+13])

Let $(\mathcal{K}, \oplus), (\mathcal{Y}, +)$ be groups. Then, a keyed function $F: \mathcal{K} \times \mathcal{X} \to \mathcal{Y}$ is a key-homomorphic PRF if F is a secure PRF and for every key $k_1, k_2 \in \mathcal{K}$ and every input $x \in \mathcal{X}$, we have

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$$\text{Update}\colon\ m \longrightarrow \boxed{F(\Delta_2, \cdot)}$$

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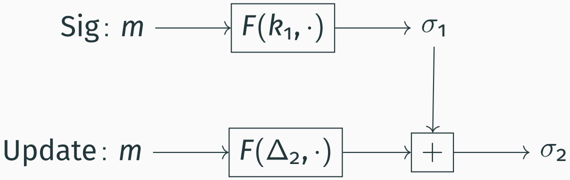

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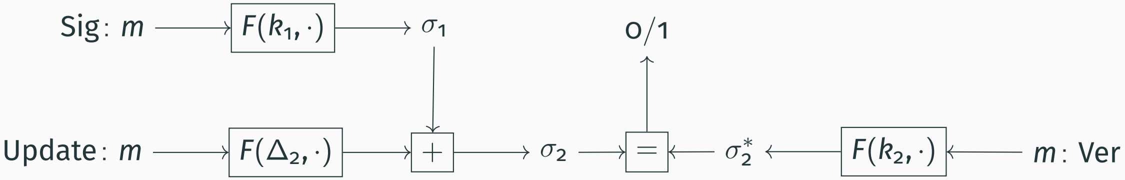

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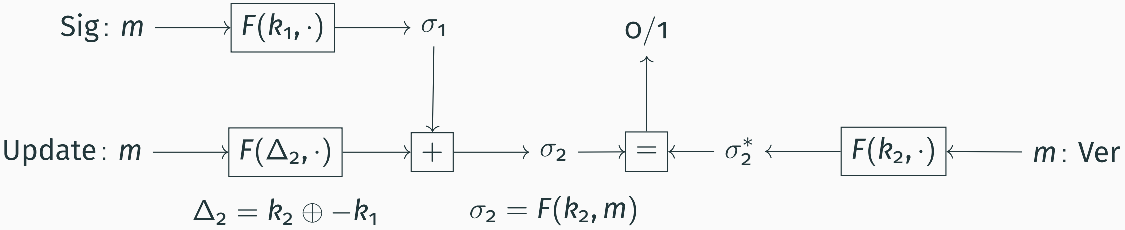
$$F(k_1, x) + F(k_2, x) = F(k_1 \oplus k_2, x) \ + e$$



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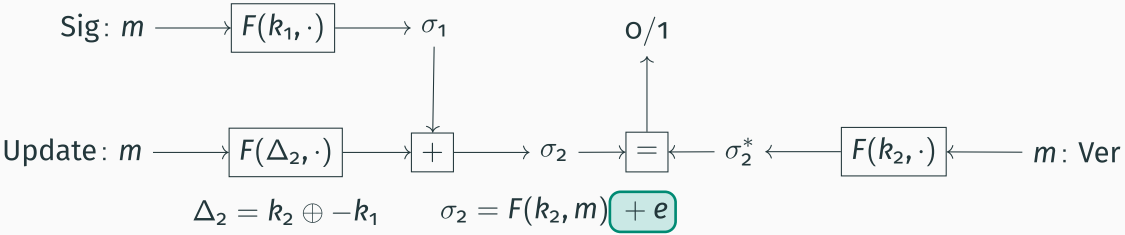

UMAC from (almost) key-homomorphic PRFs

Definition (Almost Key-Homomorphic PRFs [Bon+13])

Let $(\mathcal{K}, \oplus), (\mathcal{Y}, +)$ be groups. Then, a keyed function $F: \mathcal{K} \times \mathcal{X} \to \mathcal{Y}$ is an almost key-homomorphic PRF if F is a secure PRF and for every key $k_1, k_2 \in \mathcal{K}$ and every input $x \in \mathcal{X}$, we have

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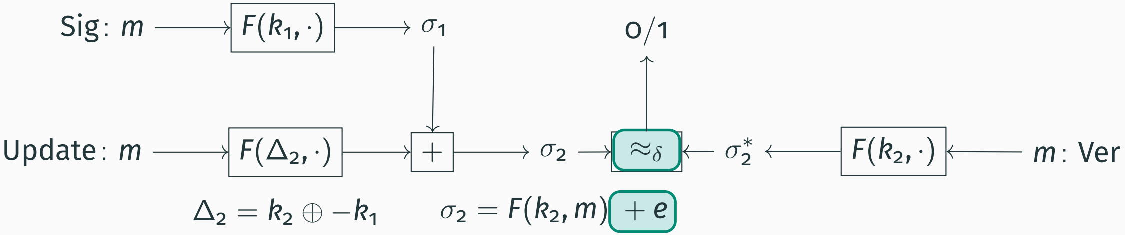

Security Proof

- Reduce UX-EUF-CMA to EUF-CMA of X for $\mathsf{X} \in \{\text{MAC}, \text{S}\}$

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  - No key inside the insulated region is corrupted
  - Tokens “on” the borders of the insulated region are not corrupted
  - All tokens inside the insulated region are corrupted

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	sk_3	sk_4	sk_5	sk_6	sk_7	sk_8
	Δ_2	Δ_3	Δ_4	Δ_5	Δ_6	Δ_7	Δ_8
σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8

- Reduce U**X**-EUF-CMA to EUF-CMA of **X** for **X** $\in$ {MAC, S}
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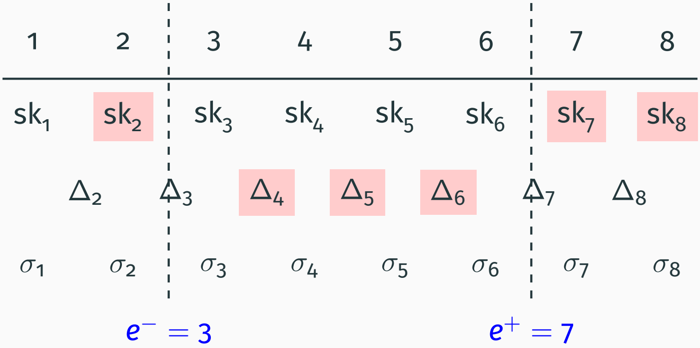

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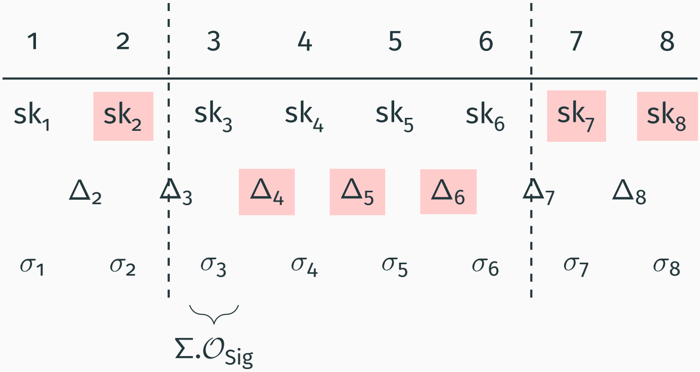
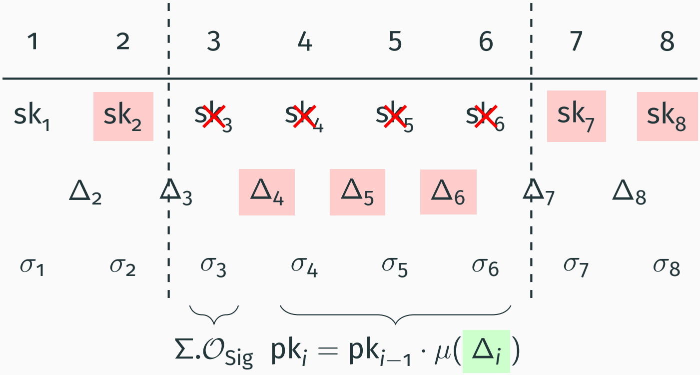


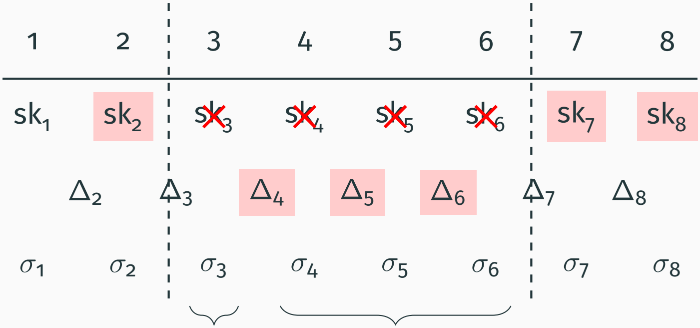
- Associate the EUF-CMA challenger of Σ to an epoch within region (e.g., to $\boldsymbol{e}^-$)

Security Proof



- Associate the EUF-CMA challenger of Σ to an epoch within region (e.g., to $\boldsymbol{e}^{-}$)
- Set keys for each epoch within the insulated region (using random $\Delta_i \leftarrow_{\$} \mathcal{T}$)

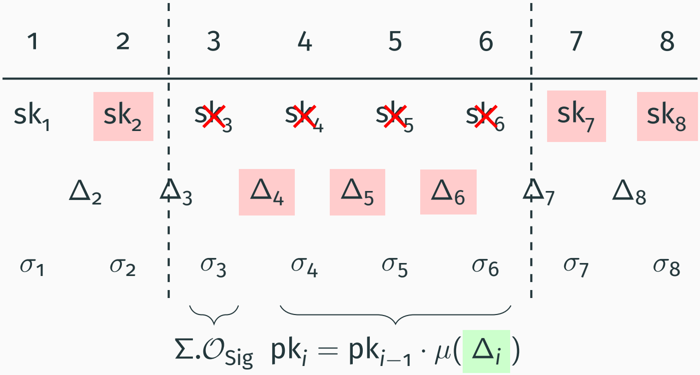
Security Proof



$\Sigma.\mathcal{O}_{\mathsf{Sig}}$ $\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)$

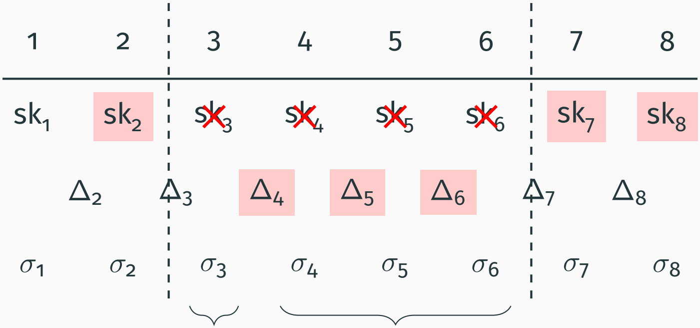
- Associate the EUF-CMA challenger of Σ to an epoch within region (e.g., to $\boldsymbol{e}^-$)
- Set keys for each epoch within the insulated region (using random $\Delta_i \leftarrow_\$ \mathcal{T}$)
- Use the EUF-CMA challenger of Σ and **Σ.Adapt** algorithm to answer queries

Security Proof



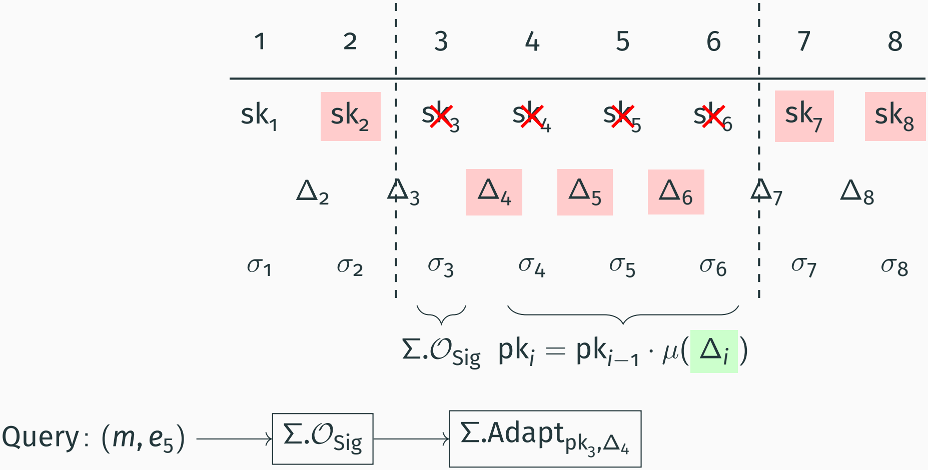
Query: (m, e_5)

Security Proof

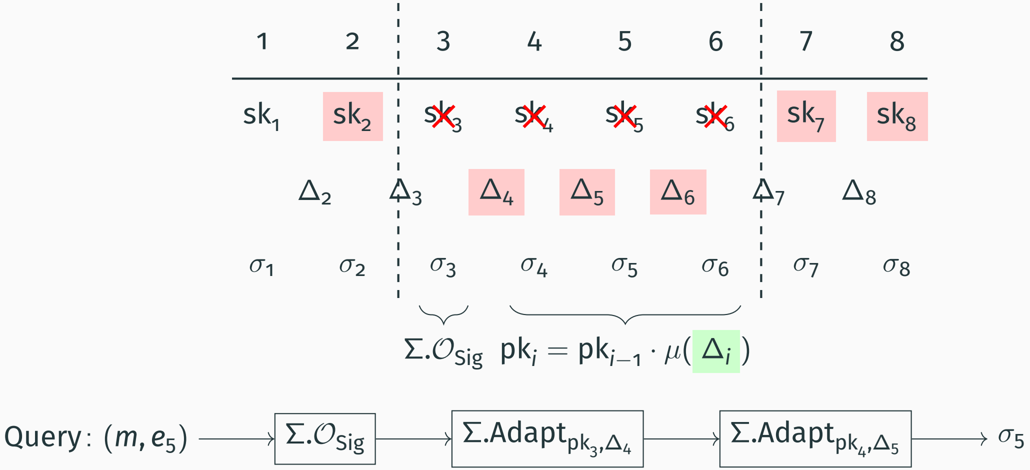


$\Sigma.\mathcal{O}_{\mathsf{Sig}}$ $\quad \mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)$

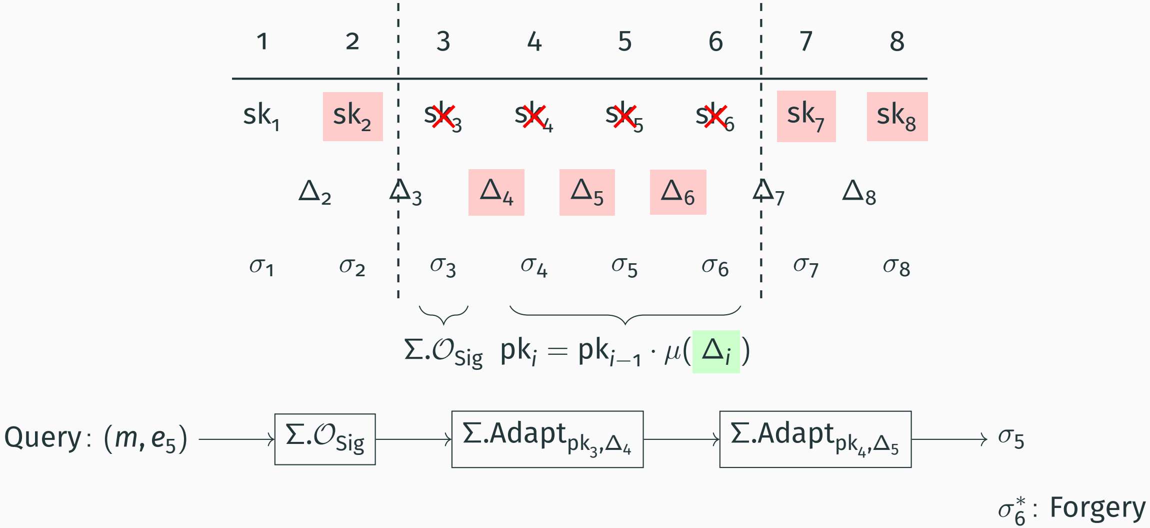
Query: $(m, e_5) \longrightarrow$ $\boxed{\Sigma.\mathcal{O}_{\mathsf{Sig}}}$

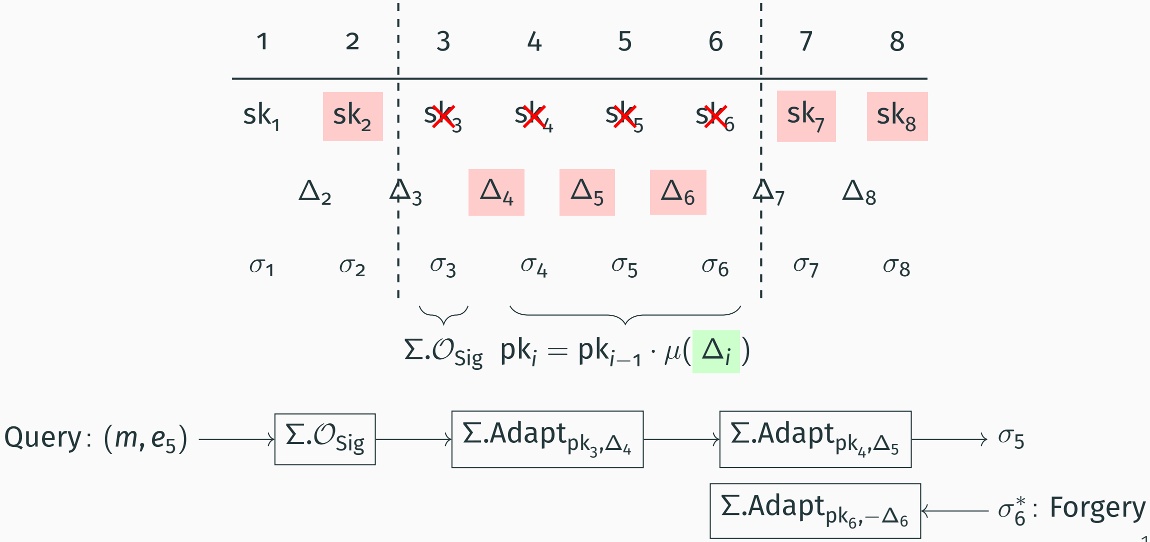

1 2 3 4 5 6 7 8
sk1 sk2 sk3 sk4 sk5 sk6 sk7 sk8
Δ2 Δ3 Δ4 Δ5 Δ6 Δ7 Δ8
σ1 σ2 σ3 σ4 σ5 σ6 σ7 σ8
Σ.OSig
pki = pki−1 · μ(Δi)
Query: (m, e5)
Σ.OSig
Σ.Adaptpk3,Δ4

Security Proof

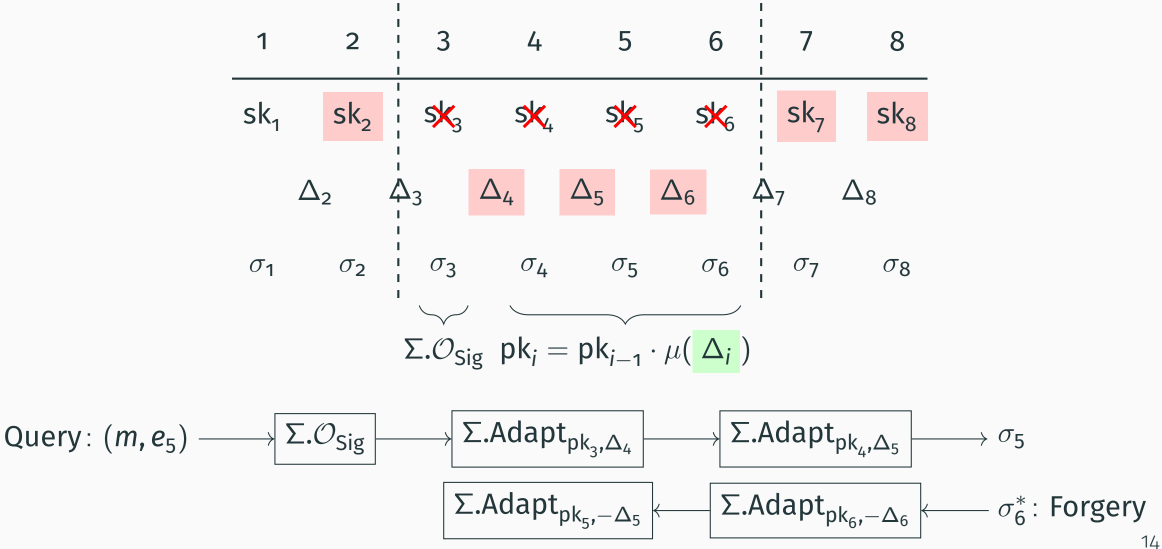


Security Proof

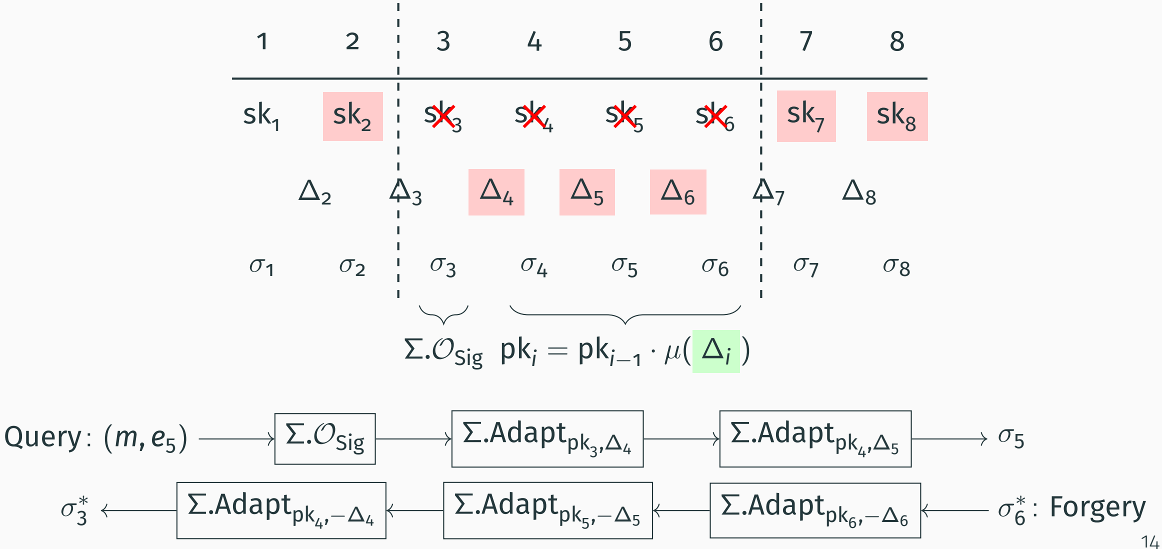



1 2 3 4 5 6 7 8
sk1 sk2 sk3 sk4 sk5 sk6 sk7 sk8
Δ2 Δ3 Δ4 Δ5 Δ6 Δ7 Δ8
σ1 σ2 σ3 σ4 σ5 σ6 σ7 σ8
Σ.OSig
pki = pki−1 · μ(Δi)
Query: (m, e5)
Σ.OSig
Σ.Adaptpk3,Δ4
Σ.Adaptpk4,Δ5
σ5
Σ.Adaptpk6,−Δ6
σ6*: Forgery

Security Proof



Security Proof



Overview and Instantiations

Updatable Signatures

Table 1: Overview of updatable signature schemes.

Scheme	Assumption	Model	UU-CMA	MD/MI	UB
BLS	co-CDH	RO	✓	MI	✓
BLS	co-CDH	RO	✓	MD	✓
PS	P-LRSW	GGM	✓	MI	✓
PS	P-LRSW	GGM	✓	MD	✓
Waters	co-CDH	SM	✓	MD	✓
GPV[1]	SIS	RO	✗	MI	T

[1]Provides US-EUF-CMA security only in a weakened model.

Table 2: Overview of updatable MAC schemes.

Scheme	Assumption	Model	UU-CMA	MD/MI	UB
BLMR (NPR) [Bon+13]	DDH	RO	✓	MD	✓
NPR	DDH	RO	✓	MI	✓
BEKS [Bon+20]	RLWE	RO	✓	MD	T
Kim [Kim20]	LWE	SM	✓	MD	T

Conclusion and Open Questions

Conclusion

- New cryptographic primitives, UMAC and US

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Conclusion

- New cryptographic primitives, UMAC and US
- Generic constructions from KH-PRF and KH-Sig
- Message independent constructions
- Post-quantum instantiations from lattices

Open Questions

- Construction of lattice-based US with full security?
- Concrete bounds for UMAC from almost KH-PRFs?

Thank you for your attention!

(full version of the paper available on ePrint: ia.cr/2021/365)

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