Updatable Signatures and Message Authentication Codes

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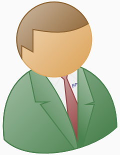
Motivation

- 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).

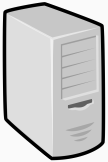
Our Framework

Definition

epoch e

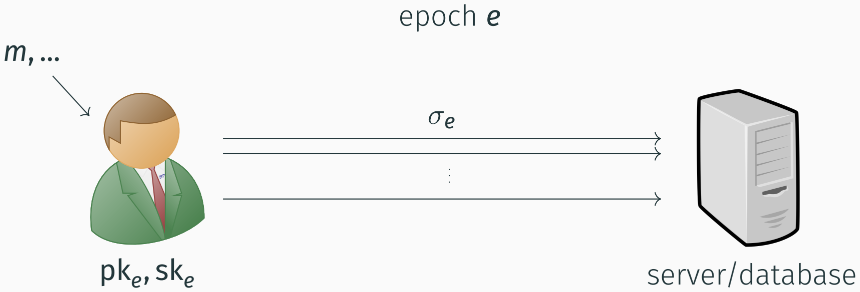


$\mathsf{pk}_e, \mathsf{sk}_e$



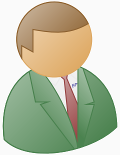
server/database

Definition



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

epoch e



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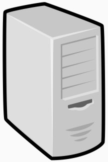
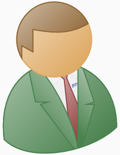


σ_e

server/database

Definition

epoch e

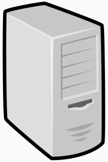


~~$\mathsf{pk}_e, \mathsf{sk}_e$~~

$$\xrightarrow{pk_e, sk_e}$$

$\boxed{\text{Next}}$

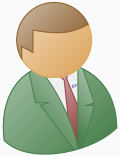
σ_e



server/database

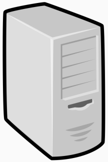
Definition

epoch $e+1$



$\cancel{\mathrm{pk}_e, \mathrm{sk}_e}$

$\mathrm{Next} \xrightarrow{pk_{e+1}, sk_{e+1}, \Delta_{e+1}}$



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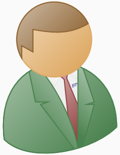
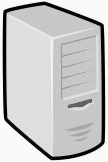


$\mathsf{pk}_{e+1}, \mathsf{sk}_{e+1}$

Δ_{e+1}



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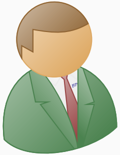

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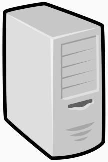

server/database

σ_e

σ_{e+1}

$\boxed{\text{Update}}$

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.

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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}
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}

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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 $(\mathbb{G}, p, g)$

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

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

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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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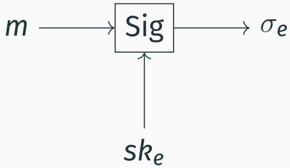
Example: [BLS01]

$$m \longrightarrow \boxed{\mathsf{Sig}}^{\,\downarrow sk} \longrightarrow \sigma = H(m)^{sk} \longrightarrow \boxed{\mathsf{Adapt}}^{\,\downarrow pk, m, \Delta} \longrightarrow \begin{array}{l} pk' = pk \cdot g^{\Delta} \\ \sigma' = \sigma \cdot H(m)^{\Delta} \end{array}$$

KH-based construction



$$
\begin{tikzcd}
m \arrow[r] & \boxed{\mathsf{Sig}} \arrow[r] & \sigma_e & \\
& sk_e \arrow[u] \arrow[rr] & & \boxed{\mathsf{Next}}
\end{tikzcd}
$$

$$
\Delta_{e+1} \leftarrow \mathbb{H}; \quad \begin{aligned} pk_{e+1} &:= pk_e \cdot \mu(\Delta_{e+1}) \\ sk_{e+1} &:= sk_e + \Delta_{e+1} \end{aligned}
$$

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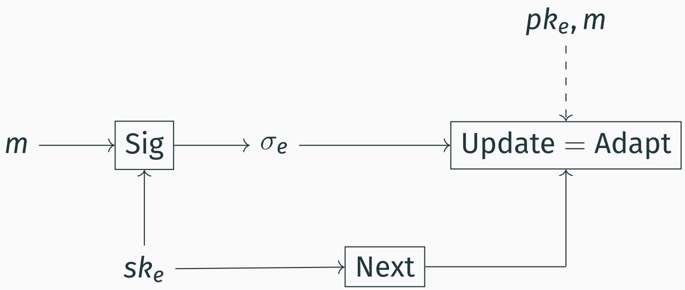

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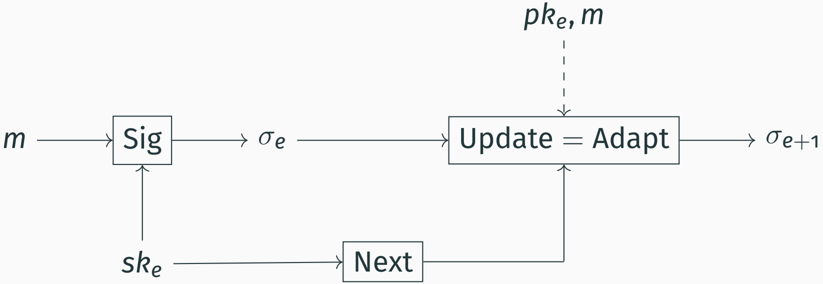

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Lattice-based candidate construction (1/2)

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

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By using methods inspired by the lattice-based proxy re-signature approach of Fan and Liu [FL19], we obtain a candidate lattice-based US signature.

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Let F be a secure PRF, then we can construct a canonical MAC from it

UMAC from (almost) key-homomorphic PRFs

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 & & & 0/1 & & &
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Definition (Key-Homomorphic PRFs [Bon+13])

Let $(\mathcal{K}, \oplus), (\mathcal{Y}, +)$ be groups. Then, a keyed function $F\colon \mathcal{K} \times \mathcal{X} \to \mathcal{Y}$ 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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$$\mathrm{Update}\colon\ m \longrightarrow \boxed{F(\Delta_2, \cdot)}$$

$$\Delta_2 = k_2 \oplus -k_1$$

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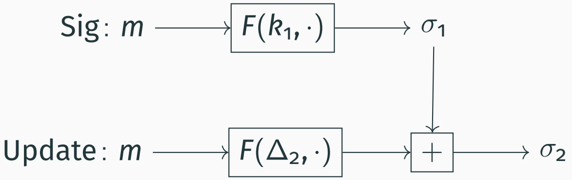

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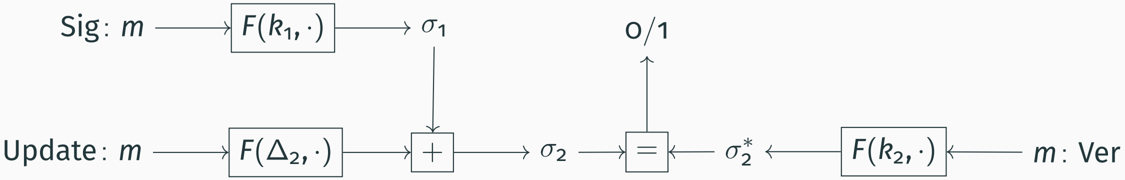

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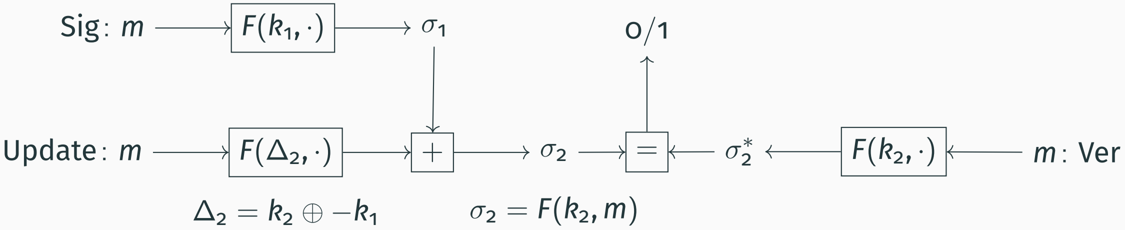
$$F(k_1, x) + F(k_2, x) = F(k_1 \oplus k_2, x) \ + e$$



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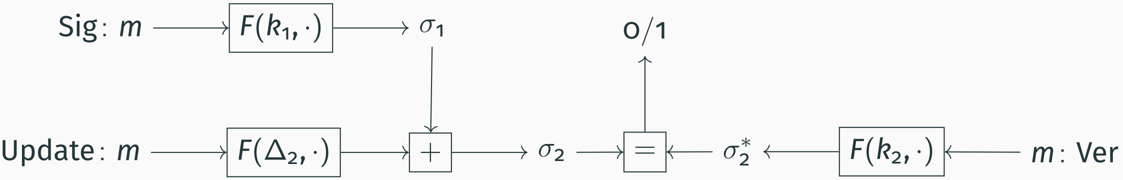
Definition (Almost Key-Homomorphic PRFs [Bon+13])

Let $(\mathcal{K}, \oplus), (\mathcal{Y}, +)$ be groups. Then, a keyed function $F\colon \mathcal{K} \times \mathcal{X} \to \mathcal{Y}$ 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

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



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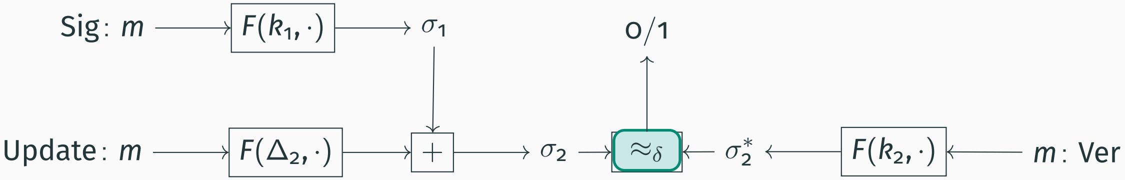

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Security Proof

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- Key insulation technique of Klooß et al. [KLR19] (i.e., region $[e^-, e^+[$):
  - 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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$e^- = 3$ $\quad$ $e^+ = 7$

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$\Sigma.\mathcal{O}_{\mathsf{Sig}}$

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

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}}$ $\underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)}$

- 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 $\Delta_i \leftarrow_{\$} \mathcal{T}$)

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

$$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \quad \underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)}$$

- 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

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

$$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \quad \underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\boxed{\Delta_i})}$$

Query: (m, e_5)

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	sk_7	sk_8
	Δ_2	Δ_3	Δ_4	Δ_5	Δ_6	Δ_7	Δ_8
σ_1	σ_2	$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}}$	σ_4	σ_5	σ_6	σ_7	σ_8

$$\underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)}$$

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

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

$$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \quad \underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)}$$

Query: $(m, e_5) \longrightarrow \boxed{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \longrightarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_3,\Delta_4}}$

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

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$$\text{Query}: (m, e_5) \longrightarrow \boxed{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \longrightarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_3,\Delta_4}} \longrightarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_4,\Delta_5}} \longrightarrow \sigma_5$$

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	sk_7	sk_8
	Δ_2	Δ_3	Δ_4	Δ_5	Δ_6	Δ_7	Δ_8
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σ_6^*: Forgery

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	sk_7	sk_8
	Δ_2	Δ_3	Δ_4	Δ_5	Δ_6	Δ_7	Δ_8
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$$\boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_6,-\Delta_6}} \longleftarrow \sigma_6^* : \text{Forgery}$$

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

$$\underbrace{\sigma_3}_{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \quad \underbrace{\sigma_4 \quad \sigma_5 \quad \sigma_6}_{\mathsf{pk}_i = \mathsf{pk}_{i-1} \cdot \mu(\Delta_i)}$$

$$\text{Query}: (m, e_5) \longrightarrow \boxed{\Sigma.\mathcal{O}_{\mathsf{Sig}}} \longrightarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_3,\Delta_4}} \longrightarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_4,\Delta_5}} \longrightarrow \sigma_5$$

$$\boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_5,-\Delta_5}} \longleftarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_6,-\Delta_6}} \longleftarrow \sigma_6^* : \text{Forgery}$$

Security Proof

1	2	3	4	5	6	7	8
sk_1	sk_2	$\cancel{\mathsf{sk}_3}$	$\cancel{\mathsf{sk}_4}$	$\cancel{\mathsf{sk}_5}$	$\cancel{\mathsf{sk}_6}$	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

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$$\sigma_3^* \longleftarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_4,-\Delta_4}} \longleftarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_5,-\Delta_5}} \longleftarrow \boxed{\Sigma.\mathsf{Adapt}_{\mathsf{pk}_6,-\Delta_6}} \longleftarrow \sigma_6^*: \text{Forgery}$$

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

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- 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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Supported by:

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