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The Direction of Updatable Encryption does not Matter Much

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Updatable Encryption

Problem Motivation: Outsourcing

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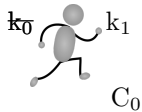
$\mathrm{Dec}_{k_0}(C_0) = m$

— Threats: Key compromise

Problem Motivation: Outsourcing

- Threats: Key compromise
- Solution: Key rotation

Key Rotation: a Standard Approach



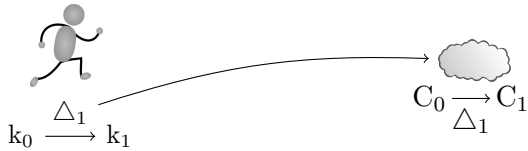
C_0 ← Download

Decrypt m = $Dec_{k_0}(C_0)$

Re-encrypt $Enc_{k_1}(m) = C_1$ → Re-upload → C_1

— Download and re-upload is infeasible
even for moderate storage requirements

Key Rotation: Updatable Encryption (UE)



— **Key Homomorphic PRFs and their Applications**
Boneh, Lewi, Montgomery, Raghunathan; CRYPTO '13 (+ ePrint 2015/220)

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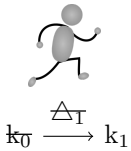
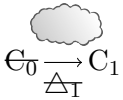
Key Rotation: Updatable Encryption (UE)





— Client only ever needs to store one key

— fresh encryptions, updated ciphertexts and tokens should all reveal nothing about plaintext

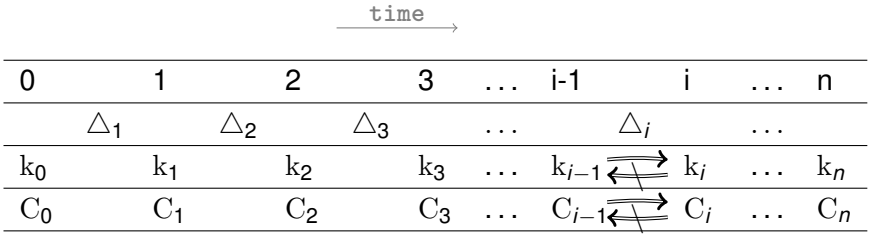
— **Key Homomorphic PRFs and their Applications**
Boneh, Lewi, Montgomery, Raghunathan; CRYPTO '13 (+ ePrint 2015/220)

Epoch-based Model

time →

0	1	2	3	4	5	6	7	...	n
	$\triangle_1$	$\triangle_2$	$\triangle_3$	$\triangle_4$	$\triangle_5$	$\triangle_6$	$\triangle_7$	...	
k_0	k_1	k_2	k_3	k_4	k_5	k_6	k_7	...	k_n
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	...	C_n

Uni-directional Updates



Uni-directional key updates:

- We can only infer k_i from k_{i-1} and $\triangle_i$;
- We can not infer k_{i-1} from k_i and $\triangle_i$;

Uni-directional ciphertext updates:

- We can only infer C_i from C_{i-1} and $\triangle_i$;
- We can not infer C_{i-1} from C_i and $\triangle_i$;

Bi-directional Updates

time →

0		1		2		3	...	i-1		i	...	n
	$\triangle_1$		$\triangle_2$		$\triangle_3$		...		$\triangle_i$		...	
k_0		k_1		k_2		k_3	...	k_{i-1}	⇄	k_i	...	k_n
C_0		C_1		C_2		C_3	...	C_{i-1}	⇄	C_i	...	C_n

Bi-directional key updates:

- We can infer k_i from k_{i-1} and $\triangle_i$;
- We can infer k_{i-1} from k_i and $\triangle_i$;

Bi-directional ciphertext updates:

- We can infer C_i from C_{i-1} and $\triangle_i$;
- We can infer C_{i-1} from C_i and $\triangle_i$;

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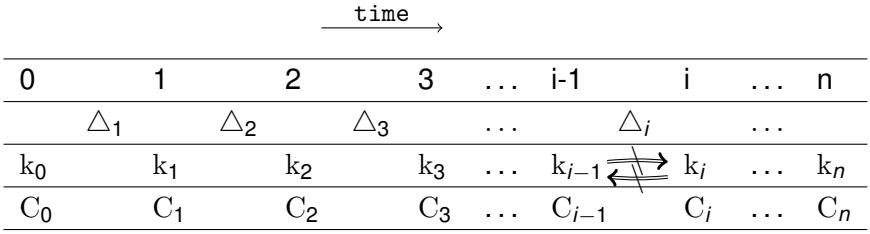
Questions

— UE schemes with uni-directional updates leak less information than with bi-directional updates

— Are uni-directional updates better?

No-directional Key Updates



No-directional key updates:

— We can not infer k_i from k_{i-1} and $\triangle_i$;

— We can not infer k_{i-1} from k_i and $\triangle_i$;

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Questions

- UE schemes with no-directional key updates leak the least information
- Are no-directional key updates better?

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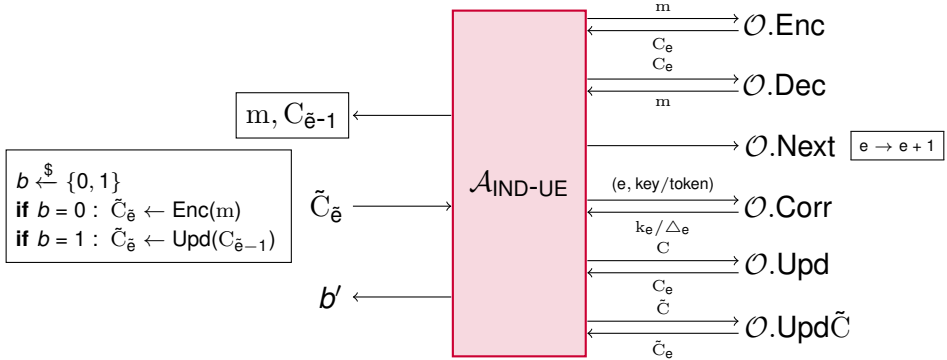
Security Notions

Existing Confidentiality Notions for Updatable Encryption (IND-UE)

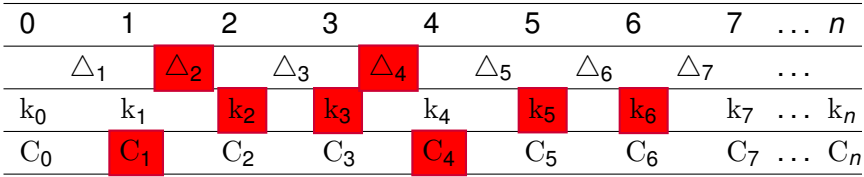


— Challenger checks leaked information to see if the adversary can trivially win

Only in CCA games does an adversary have access to $\mathcal{O}$.Dec

— **Fast and Secure Updatable Encryption**
Boyd, Davies, Gjøsteen, Jiang; Crypto '20

Leakage and Trivial Wins



— Directly obtained information:

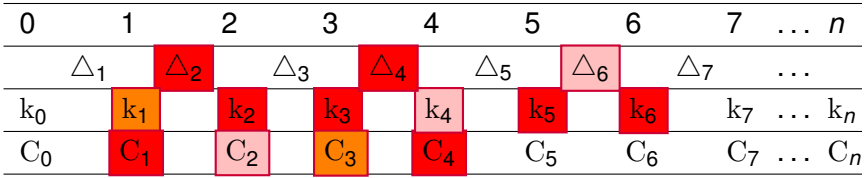
- Adversary adaptively corrupts keys and tokens
- Adversary can asks for ciphertexts

Corrupted information

Inferred information

Inferred information (only in bi-directional updates)

Leakage and Trivial Wins

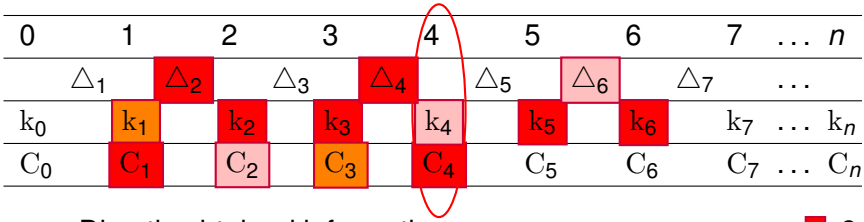


— Directly obtained information:
- Adversary adaptively corrupts keys and tokens
- Adversary can asks for ciphertexts

— Inferred information:
- Assume uni-directional updates: $k_4, \triangle_6, C_2$.
- Assume bi-directional updates: $k_1, k_4, \triangle_6, C_2, C_3$.

Corrupted information
Inferred information
Inferred information (only in bi-directional updates)

Leakage and Trivial Wins

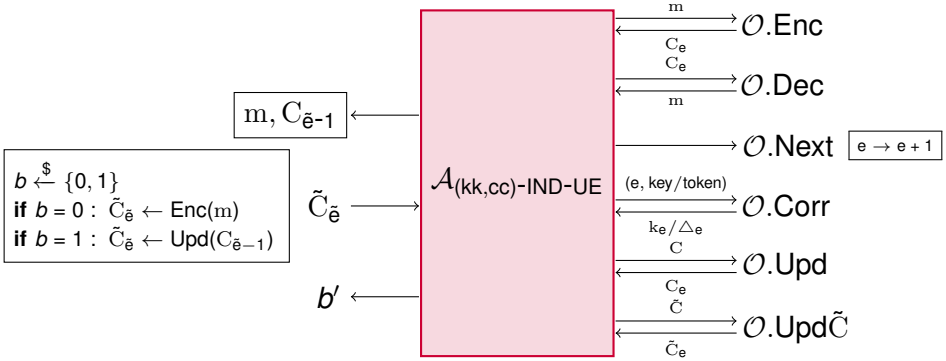


- Directly obtained information:
  - Adversary adaptively corrupts keys and tokens
  - Adversary can asks for ciphertexts
- Inferred information:
  - Assume uni-directional updates: $k_4, \triangle_6, C_2$.
  - Assume bi-directional updates: $k_1, k_4, \triangle_6, C_2, C_3$.
- Adversary can use k_4 to decrypt C_4 to trivially win a security game!

Corrupted information
Inferred information
Inferred information (only in bi-directional updates)

Six Variants of Confidentiality Notions

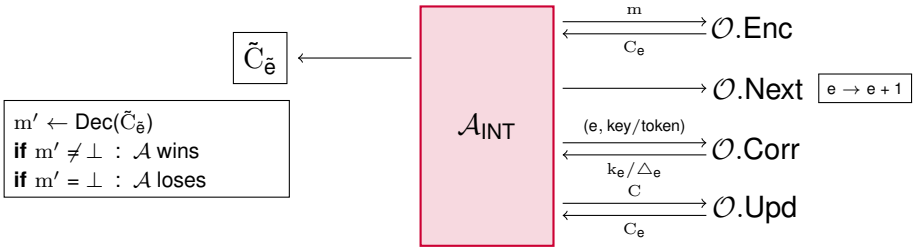
— For kk $\in \{\text{uni}, \text{bi}, \text{no}\}$ and cc $\in \{\text{uni}, \text{bi}\}$, consider UE schemes with kk-directional key updates and cc to cc-directional ciphertext updates.



— Challenger checks leaked information to see if the adversary can trivially win

— Trivial wins depend on the update settings!

Existing Integrity Notions for Updatable Encryption

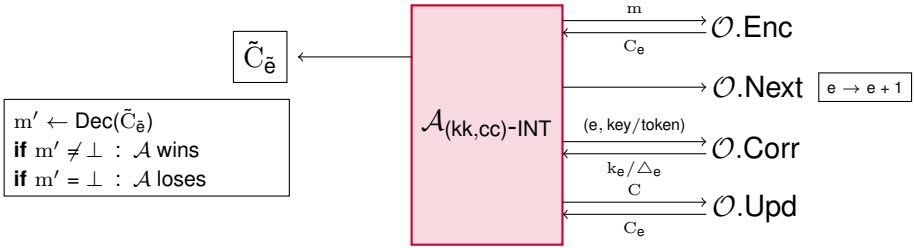


— Challenger checks leaked information to see if the adversary can trivially win

— **(R)CCA secure updatable encryption with integrity protection**
Klooß, Lehmann and Rupp; Eurocrypt '19

Six Variants of Integrity Notions

— For kk $\in \{\text{uni}, \text{bi}, \text{no}\}$ and cc $\in \{\text{uni}, \text{bi}\}$, consider UE schemes with kk-directional key updates and cc to cc-directional ciphertext updates.



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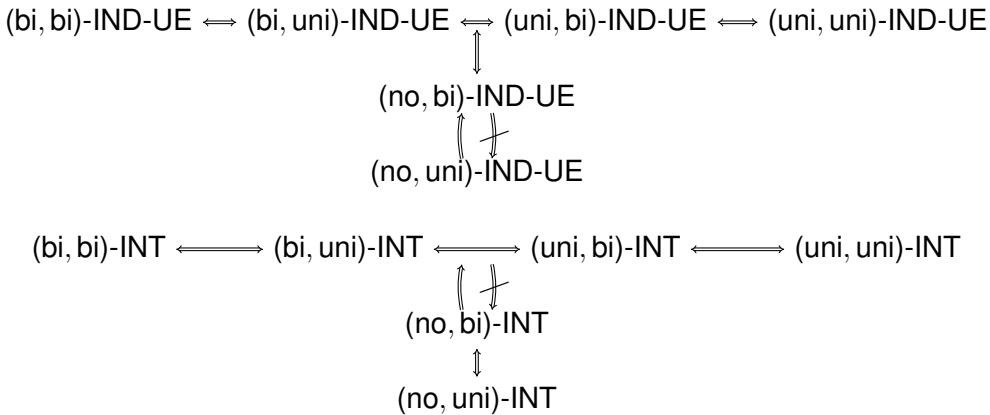
Relations

Relations


(bi, bi)-IND-UE
(bi, uni)-IND-UE
(uni, bi)-IND-UE
(uni, uni)-IND-UE
(no, bi)-IND-UE
(no, uni)-IND-UE
(bi, bi)-INT
(bi, uni)-INT
(uni, bi)-INT
(uni, uni)-INT
(no, bi)-INT
(no, uni)-INT

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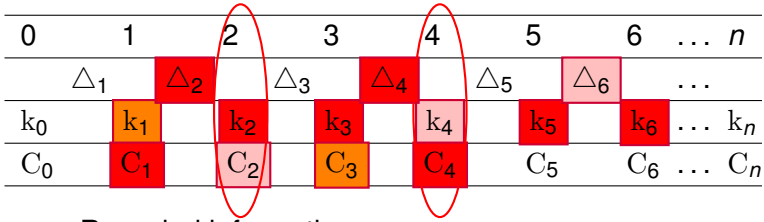
How to prove these relations?

— To prove:
  - Security notions with uni- and bi-directional updates are equivalent.

— It suffices to prove:
  - The trivial wins in the uni-directional updates are triggered if and only if the trivial wins in the bi-directional updates are triggered.

Motivation Example | Uni-directional vs. Bi-directional



Corrupted information

Inferred information

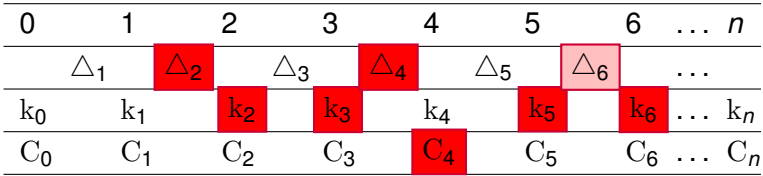
Inferred information (only in bi-directional updates)

— Revealed information:
  - Assume uni-directional updates: $k_2, k_3, k_4, k_5, k_6, \triangle_2, \triangle_4, \triangle_6$.
  - Assume bi-directional updates: $k_1, k_2, k_3, k_4, k_5, k_6, \triangle_2, \triangle_4, \triangle_6$.

— Adversary can trivially win a security game if it asks for one of $C_1, \ldots, C_6$! No matter uni- or bi-directional updates!

— UE schemes with uni-directional updates will not provide more security than UE schemes with bi- directional updates!

Motivation Example | No-directional Key Updates and Uni-directional Ciphertext Updates



Corrupted information
Inferred information
Inferred information (only in bi-directional updates)

— Adversary can not trivialliy win the confidentiality game!

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UE Constructions

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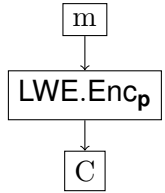
Prior Works

UE schemes	Hard problems	IND-UE
BLMR	DDH or LWE, etc.	✘
RISE	DDH	✓
NYUAE	SXDH	✓?
E&M	DDH	✓?
SHINE	DDH	✓

— Can we find post-quantum secure UE schemes?

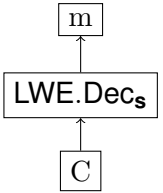
An LWE-based UE scheme (LWEUE)

LWEUE.Enc :



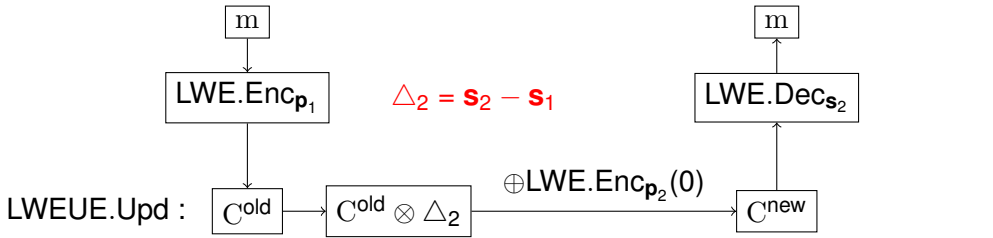
$C = \text{LWE.Enc}_p(m)$

LWEUE.Dec :



$m = \text{LWE.Dec}_s(C)$

An LWE-based UE scheme (LWEUE): Re-randomization



LWEUE is randIND-UE-CPA Secure

Assuming DLWE

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Summary

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Summary

- We introduce six-variants of security notions for UE schemes.
- Security notions with uni- and bi-directional updates are equivalent. A surprising result!
- Security notions with no-directional key updates are strictly stronger than uni- and bi- directional update variants of the corresponding notions.
- A post-quantum secure UE scheme: LWEUE

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Open Problems

— Constructing UE schemes with no-directional key updates.

— Constructing UE schemes with chosen ciphertext post-quantum security.

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Thank you for your attention!

Questions?