Structure-Preserving Chosen-Ciphertext Security with Shorter Verifiable Ciphertexts

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Smooth combination with Groth-Sahai (NIWI) proofs.
(witness extraction always possible)

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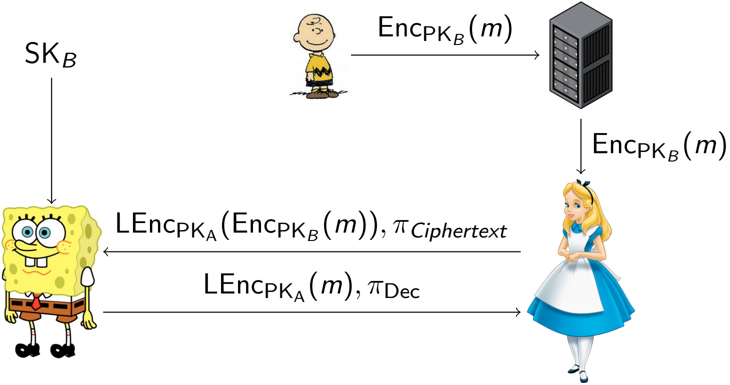
Example

1. Secure blind decryption [Gre11]
2. Oblivious 3rd parties protocols [CGH08]

Secure blind decryption [Gre11]



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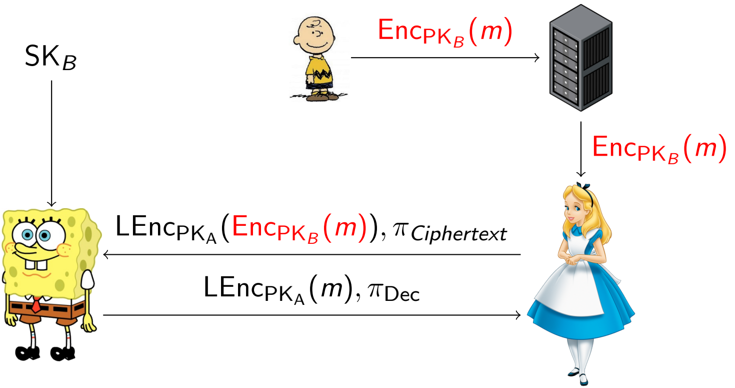
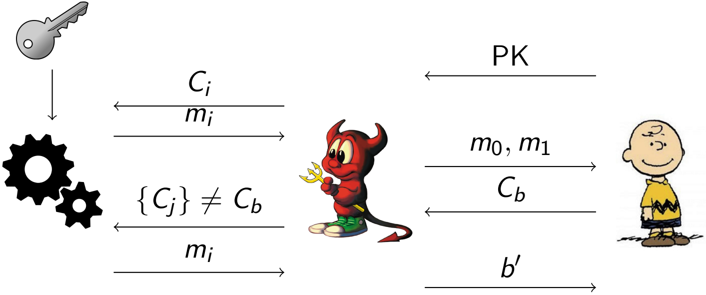


Public verifiability

- Allows adaptive OT with public contribution to database.
- Allows everyone to check the sanity of the database.
- Makes it possible to distribute senders.

Indistinguishable Chosen-Ciphertext security (IND-CCA)

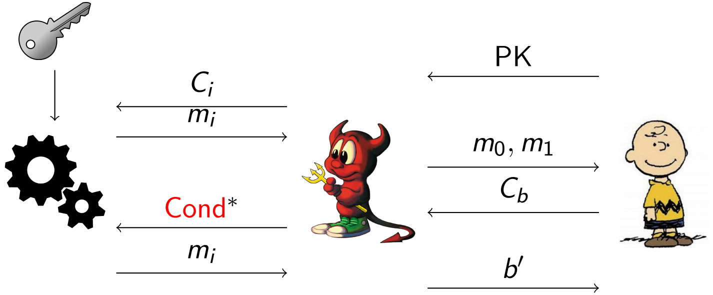
IND-CCA



Advantage: $Adv(\mathcal{A}) = |\Pr[b = b'] - \frac{1}{2}|.$

Replayable Chosen-Ciphertext security (RCCA)

RCCA



Advantage: $Adv(\mathcal{A}) = |\Pr[b = b'] - \frac{1}{2}|$.

- Motivation: Compatible with perfect rerandomizable encryption scheme.
- Optimal security notion for rerandomizable encryption schemes

* $Dec(k_d, \{C_j\}) \notin \{m_0, m_1\}$

Type-3 pairings and DDH (SXDH) assumption

Pairing

For three groups $(\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T)$ of prime order p and $e : \mathbb{G} \times \hat{\mathbb{G}} \to \mathbb{G}_T$.

$$e(A^\lambda, B) = e(A, B^\lambda) \qquad e(g, h) = 1 \text{ iff } g = 1 \vee h = 1$$

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DDH (SXDH) assumption

Let $g \in \mathbb{G}$ and $a, b, c \xleftarrow{R} \mathbb{Z}_p$

- Decisional Diffie-Hellman (DDH):

$$\{g, g^a, g^b, g^{ab}\} \approx_c \{g, g^a, g^b, g^c\}.$$

- Symmetric eXternal Diffie-Hellman (SXDH): DDH in $\mathbb{G}$ and $\hat{\mathbb{G}}$.

State of the art

Structure-Preserving Signatures

- [AHO10] Sign a message $\boldsymbol{M} = (m_1, m_2, \ldots, m_n) \in \hat{\mathbb{G}}^n$ with a signature $2\mathbb{G} + 5\hat{\mathbb{G}}$ under SXDH with asymmetric pairings.

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Structure-Preserving Public Key Encryption

- [CHK+11] Encryption of a message $m \in \mathbb{G}$ consists of $4\mathbb{G} + 1\mathbb{G}_T$ under DLIN with symmetric pairings; not publicly verifiable.
- [ADK+13] Structure-preserving publicly verifiable encryption with $321\mathbb{G}$ under DLIN.

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Our goals

- Shorter ciphertexts under SXDH in asymmetric pairings (most efficient configuration)
- Public verifiability

Contents

Contributions

	Ciphertext Size[†]	Assumption	Security
[ADK$^+$13]	$321 \times \mathbb{G}$[‡]	DLIN	CCA
This work	$16 \times \mathbb{G} + 11 \times \hat{\mathbb{G}}$	SXDH	CCA
[CKLM12]	$93 \times \mathbb{G}$	DLIN	RCCA
[CKLM12]	$49 \times \mathbb{G} + 20 \times \hat{\mathbb{G}}$	SXDH	RCCA
This work[§]	$29 \times \mathbb{G} + 20 \times \hat{\mathbb{G}}$	SXDH	RCCA

[†] In the asymmetric setting, we assume $|\hat{\mathbb{G}}| \approx 2 \cdot |\mathbb{G}|$.

[‡] Only instantiable with symmetric pairing

[§] Instantiation of their generic construction with the more efficient tools to date.

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Groth-Sahai Proof Systems

Only efficient NIZK proofs in the standard model for now.

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Statement: Pairing Product Equation (PPE)

$$\prod_{j=1}^{n} e(\mathcal{A}_j, \mathcal{Y}_j) \prod_{i=1}^{m} e(\mathcal{X}_i, \mathcal{B}_i) \prod_{i=1}^{m} \prod_{j=1}^{n} e(\mathcal{X}_i, \mathcal{Y}_j)^{\gamma_{i,j}} = t_T$$

Statement: Multi-Exponentiation Equation

$$\prod_{j=1}^{n} \mathcal{A}_j^{y_j} \prod_{i=1}^{m} \mathcal{X}_i^{b_i} \prod_{i=1}^{m} \prod_{j=1}^{n} \mathcal{X}_i^{\gamma_{i,j} y_j} = t_T$$

Where for $i \in \{1, \ldots, m\}$ and $j \in \{1, \ldots, n\}$

1. Variables: $\mathcal{X}_i$, $\mathcal{Y}_j$ and y_j.
2. Constants: $\mathcal{A}_j$, $\mathcal{B}_i$, t_T, $\gamma_{i,j}$ and b_i.

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- Multi-exponentiation equation.
- Operate in two modes: Depending on the Common Reference String $CRS = (\boldsymbol{u}_1, \boldsymbol{u}_2, \hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2) \in \mathbb{G}^2 \times \mathbb{G}^2 \times \hat{\mathbb{G}}^2 \times \hat{\mathbb{G}}^2$.

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A NIWI/NIZK proof system (Setup, Prove, Verify):

- Multi-exponentiation equation.
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  - Perfect Zero-Knowledge (ZK) setting $\exists \zeta, \hat{\zeta} \in \mathbb{Z}_p$ s.t. $\boldsymbol{u}_2 = \boldsymbol{u}_1^{\zeta}$ and $\hat{\boldsymbol{u}}_2 = \hat{\boldsymbol{u}}_1^{\hat{\zeta}}$.
    1. Using $\zeta, \hat{\zeta}$, we can simulate a proof for false statement.
    2. Proofs using different valid witnesses are indistinguishable.

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    1. Using $\zeta, \hat{\zeta}$, we can simulate a proof for false statement.
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  - Perfect Soundness setting $(\boldsymbol{u}_1, \boldsymbol{u}_2)$ and $(\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2)$ are independent.
    1. Even unbounded adversaries cannot prove false statements.
    2. Trapdoor allows extracting witnesses from proofs.

Strictly Structure-Preserving Commitment [AKOT15]

SSPC $(\mathsf{Setup}, \mathsf{Commit}, \mathsf{Verify})$:

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Properties

- Correctness: $\mathsf{Verify}(\mathsf{ck}, m, \mathsf{Commit}(\mathsf{ck}, m; \mathsf{open}), \mathsf{open}) = \mathsf{True}$.

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- Chosen-Message Target Collision Resistant (CM-TCR): Given $\mathsf{com}^*, m^*, \mathsf{open}^*$, hard to generate m s.t.

$$\mathsf{Verify}(\mathsf{ck}, m, \mathsf{com}^*, \mathsf{open}^*) = \mathsf{True} \wedge m \neq m^*$$

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- Enhanced Chosen-Message Target Collision Resistant (ECM-TCR):
  Given $\mathsf{com}^*, m^*, \mathsf{open}^*$, hard to generate (m, open) s.t.

$$\mathsf{Verify}(\mathsf{ck}, m, \mathsf{com}^*, \mathsf{open}) = \mathsf{True} \land (m, \mathsf{open}) \neq (m^*, \mathsf{open}^*)$$

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Construction ideas: Cramer-Shoup [CS02]

IND-CCA encryption: Cramer-Shoup

- Keys: PK $= g_1, g_2, X = g_1^{x_1} \cdot g_2^{x_2}$, SK $= x_1, x_2$.
- Ciphertext: $\boldsymbol{C} = (C_0, C_1, C_2, \pi) = (M \cdot X^r, g_1^r, g_2^r, \pi)$ where π is a proof of $log_{g_1}(C_1) = log_{g_2}(C_2)$ and $r \stackrel{R}{\leftarrow} \mathbb{Z}_q$.
- Decryption: $M = C_0/(C_1^{x_1} C_2^{x_2})$.

Proof intuitions

- Setup: PP_{GS} in perfect soundness setting.
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Construction ideas: All-but-one perfectly sound hash proof system [LY12]

ABO proof

Each proof is associated with a tag, prove with $\boldsymbol{u}_1 = \boldsymbol{u}_2 \cdot (1, \frac{1}{tag})$.

- Correct tag GS proof is in perfect soundness setting
- Wrong tag GS proof is in perfect ZK setting

Prove $log_{g_1}(C_1) = log_{g_2}(C_2)$

- Generate OTS keys $\mathsf{VK}_{OTS}, \mathsf{SK}_{OTS}$.
- Generate proof of $log_{g_1}(C_1) = log_{g_2}(C_2)$ with $tag = \mathsf{VK}_{OTS}$.

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Problems

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   - Solution: Enhanced Chosen-Message Target Collision Resistant (ECM-TCR) suffices.
2. Commitement scheme's ck and com are in $\mathbb{G}$ and $\hat{\mathbb{G}}$.
   - Solution: No need to sign the commitment. (Not trivial to prove)

Structure-Preserving Publicly Verifiable Encryption

- $\mathsf{SK} = (x_1, x_2)$.
- $\mathsf{PK} = (g_1, g_2, X = g_1^{x_1} g_2^{x_2}, \mathsf{PP}_{SPC}, \mathbf{ck}, CRS_{GS} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2) \in \hat{\mathbb{G}}^2 \times \hat{\mathbb{G}}^2)$.

where $(g_1, g_2) \in \mathbb{G}^2$, $(x_1, x_2) \in \mathbb{Z}_p^2$ and $\exists \rho_u \in \mathbb{Z}_p$ such that $\hat{\boldsymbol{u}}_1 = \hat{\boldsymbol{u}}_2^{\rho_u}$.

Details of the Encryption algorithm

- Generate $\boldsymbol{C} = (C_0, C_1, C_2) = (M \cdot X^\theta, g_1^\theta, g_2^\theta)$.
- $\mathsf{OTS.KeyGen}(\mathsf{PP}) \rightarrow (\mathsf{SSK}, \mathsf{SVK})$.
- $\mathsf{Commit}(\mathbf{ck}, \mathsf{SVK}) \rightarrow (\hat{\mathsf{com}}, \mathsf{open})$.
- Compute $\hat{\boldsymbol{u}}_{\hat{\mathsf{com}}} = \hat{\boldsymbol{u}}_2 \cdot (1, \hat{\mathsf{com}}) \in \hat{\mathbb{G}}^2$.
- $\mathsf{Prove}(CRS_{\hat{\mathsf{com}}} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_{\mathsf{com}}), (C_1, C_2), \theta) \rightarrow \pi$ of statement
$$\exists \chi \text{ s.t. } (C_1, C_2) = (g_1^\chi, g_2^\chi).$$
- $\mathsf{OTS.Sign}(\mathsf{SSK}, (\boldsymbol{C}, \pi)) \rightarrow \sigma$.
- Output the ciphertext $(\boldsymbol{C}, \pi, \mathsf{SVK}, \hat{\mathsf{com}}, \mathsf{open}, \sigma) \in \mathbb{G}^{16} \times \hat{\mathbb{G}}^{11}$.

Proof intuition

Setup

- $CRS_{GS} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2)$ with $\hat{\boldsymbol{u}}_1 = \hat{\boldsymbol{u}}_2^{\rho_u}$.

Encryption

- Generate $\boldsymbol{C}^* = (C_0^*, C_1^*, C_2^*) = (M_b \cdot X^{\theta^*}, g_1^{\theta^*}, g_2^{\theta^*})$.
- OTS.KeyGen(PP) $\rightarrow$ (SSK*, SVK*).
- Commit(**ck**, SVK*) $\rightarrow$ (côm*, open*).
- Compute $\hat{\boldsymbol{u}}_{\text{côm}} = \hat{\boldsymbol{u}}_2 \cdot (1, \text{côm}^*) \in \hat{\mathbb{G}}^2$.
- Prove($CRS_{\text{côm}} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_{\text{côm}}), x = (C_1^*, C_2^*), w = \theta^*) \rightarrow \pi^*$ of the statement "$\exists \chi$ such that $(C_1^*, C_2^*) = (g_1^{\chi}, g_2^{\chi})$".
- OTS.Sign(SSK*, $(\boldsymbol{C}^*, \pi^*)$) $\rightarrow \sigma^*$. **(No need to sign commitments)**
- Output the ciphertext $(\boldsymbol{C}^*, \pi^*, \text{SVK}^*, \text{côm}^*, \text{open}^*, \sigma^*) \in \mathbb{G}^{16} \times \hat{\mathbb{G}}^{11}$.

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- $\mathsf{OTS.KeyGen}(\mathsf{PP}) \rightarrow (\mathsf{SSK}^*, \mathsf{SVK}^*)$. Done at beginning
- $\mathsf{Commit}(\mathbf{ck}, \mathsf{SVK}^*) \rightarrow (\hat{\mathsf{com}}^*, \mathsf{open}^*)$. Done at beginning
- Compute $\hat{\boldsymbol{u}}_{\hat{\mathsf{com}}} = \hat{\boldsymbol{u}}_2 \cdot (1, \hat{\mathsf{com}}^*) \in \hat{\mathbb{G}}^2$.
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Proof intuition

Setup

- $\mathsf{OTS.KeyGen}(\mathsf{PP}) \rightarrow (\mathsf{SSK}^*, \mathsf{SVK}^*)$.
- $\mathsf{Commit}(\mathsf{ck}, \mathsf{SVK}^*) \rightarrow (\hat{\mathsf{com}}^*, \mathsf{open}^*)$.
- $CRS_{GS} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2)$ with $\hat{\boldsymbol{u}}_1 = \hat{\boldsymbol{u}}_2^{\rho_u}$.

Encryption

- Generate $\boldsymbol{C}^* = (C_0^*, C_1^*, C_2^*) = (M_b \cdot X^{\theta^*}, g_1^{\theta^*}, g_2^{\theta^*})$.
- Compute $\hat{\boldsymbol{u}}_{\hat{\mathsf{com}}} = \hat{\boldsymbol{u}}_2 \cdot (1, \hat{\mathsf{com}}^*) \in \hat{\mathbb{G}}^2$.
- Prove$(CRS_{\hat{\mathsf{com}}} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_{\hat{\mathsf{com}}}), x = (C_1^*, C_2^*), w = \theta^*) \rightarrow \pi^*$ of the statement "$\exists \chi$ such that $(C_1^*, C_2^*) = (g_1^{\chi}, g_2^{\chi})$".
- $\mathsf{OTS.Sign}(\mathsf{SSK}^*, (\boldsymbol{C}^*, \pi^*)) \rightarrow \sigma^*$. **(No need to sign commitments)**
- Output the ciphertext $(\boldsymbol{C}^*, \pi^*, \mathsf{SVK}^*, \hat{\mathsf{com}}^*, \mathsf{open}^*, \sigma^*) \in \mathbb{G}^{16} \times \hat{\mathbb{G}}^{11}$.

Proof intuition

Setup

- OTS.KeyGen(PP) $\rightarrow$ (SSK*, SVK*).
- Commit(ck, SVK*) $\rightarrow$ ($\hat{\text{com}}^*$, open*).
- $CRS_{GS} = (\hat{\boldsymbol{u}}_1, \hat{\boldsymbol{u}}_2 \cdot (1, \frac{1}{\hat{\text{com}}^*}))$ with $\hat{\boldsymbol{u}}_1 = \hat{\boldsymbol{u}}_2^{\rho_u}$.

Encryption

- Generate $\boldsymbol{C}^* = (C_0^*, C_1^*, C_2^*) = (M_b \cdot X^{\theta^*}, g_1^{\theta^*}, g_2^{\theta^*})$.
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- OTS.Sign(SSK*, ($\boldsymbol{C}^*, \pi^*$)) $\rightarrow \sigma^*$. **(No need to sign commitments)**
- Output the ciphertext $(\boldsymbol{C}^*, \pi^*, \text{SVK}^*, \hat{\text{com}}^*, \text{open}^*, \sigma^*) \in \mathbb{G}^{16} \times \hat{\mathbb{G}}^{11}$.

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- Generate $\boldsymbol{C}^* = (C_0^*, C_1^*, C_2^*) = (M_b \cdot C_1^{x_1} \cdot C_2^{x_2}, g_1^{\theta^*}, g_2^{\theta^*})$.
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Encryption

- Generate $\boldsymbol{C}^* = (C_0^*, C_1^*, C_2^*) = (M_b \cdot C_1^{x_1} \cdot C_2^{x_2}, g_1^{\theta_1}, g_2^{\theta_2})$.
- Compute $\hat{\boldsymbol{u}}_{\hat{\mathsf{com}}} = \hat{\boldsymbol{u}}_2 \cdot (1, \hat{\mathsf{com}}^*) \in \hat{\mathbb{G}}^2$.
- Simulate proof of the false statement $log_{g_1}(C_1) = log_{g_2}(C_2)$ using ρ_u.
- $\mathsf{OTS.Sign}(\mathsf{SSK}^*, (\boldsymbol{C}^*, \pi^*)) \to \sigma^*$. **(No need to sign commitments)**
- Output the ciphertext $(\boldsymbol{C}^*, \pi^*, \mathsf{SVK}^*, \hat{\mathsf{com}}^*, \mathsf{open}^*, \sigma^*) \in \mathbb{G}^{16} \times \hat{\mathbb{G}}^{11}$.

Conclusion

- Publicly verifiable IND-CCA encryption: $321\mathbb{G} \to 16\mathbb{G} + 11\hat{\mathbb{G}}$.
- Publicly verifiable RCCA rerandomizable encryption: $93\mathbb{G}/49\mathbb{G} + 20\hat{\mathbb{G}} \to 29\mathbb{G} + 20\hat{\mathbb{G}}$.

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Future Works

- Smaller ciphertext for rerandomization encryption scheme.
- More general malleability (e.g. Linear Homomorphism, HCCA security)?

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