Practical Fully Secure Inner Product Functional Encryption modulo p

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Functional Encryption (FE)

Functional Encryption [BSW11]

Alice

m

Auth.

Setup

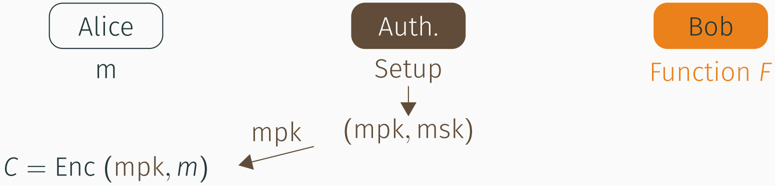
↓

(mpk, msk)

Bob

Function F

Functional Encryption [BSW11]



Functional Encryption [BSW11]

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	$\downarrow$ (mpk, msk)
$C = \text{Enc}(\text{mpk}, m)$	$\text{sk}_F = \text{KeyDer}(\text{msk}, F)$ $\xleftarrow{F}$ $\xrightarrow{\text{sk}_F}$	sk_F

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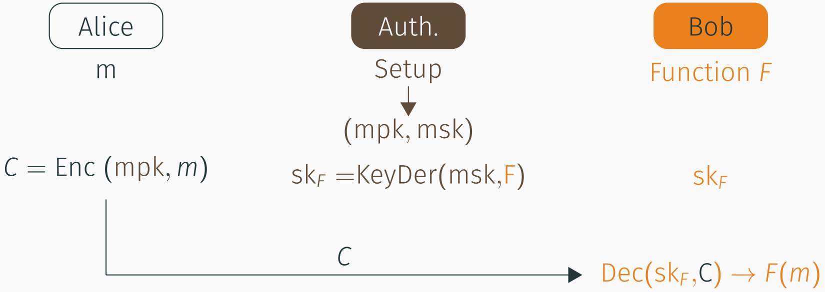

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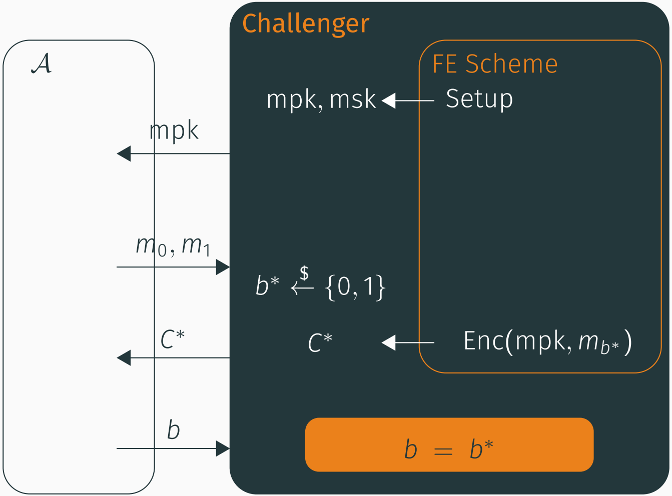
	(mpk, msk)	
$C = \text{Enc}(\text{mpk}, m)$	$\text{sk}_F = \text{KeyDer}(\text{msk}, F)$	sk_F
		$\text{Dec}(\text{sk}_F, C) \rightarrow F(m)$

Bob **only learns** $F(m)$.

FE Security – Indistinguishability



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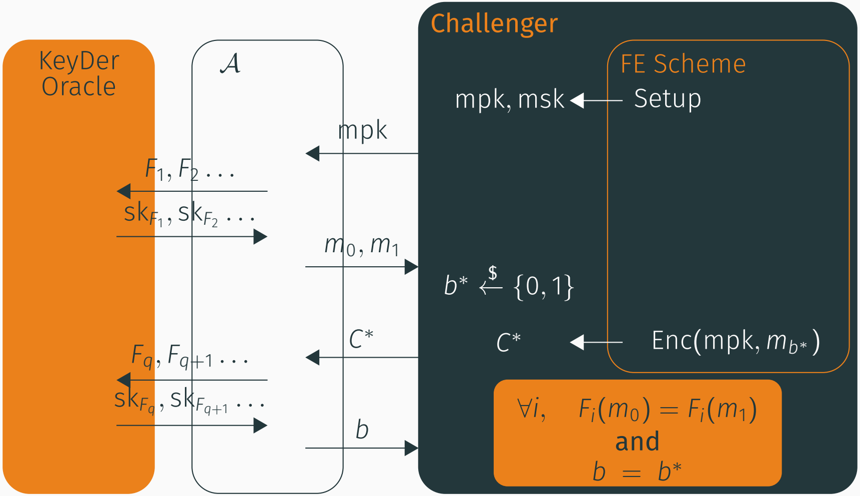

Limits of General Functional Encryption

Constructions of FE for **general functions** exist, but are **not practical**

[SS10, GVW12, GKP+13a, GKP+13b, ABSV15, Wat15, BGJS16, GGHZ16]

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$\Rightarrow$ **Linear Functions:** simple with many applications

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$\Rightarrow$ **Linear Functions:** simple with many applications

- Understand general FE
- Statistical analysis on encrypted data
- Evaluation of polynomials over encrypted data [KSW08]
- Constructing trace-and-revoke systems [ABP+17]
- etc.

The Inner Product Functionality

The inner product functionality

Auth.

Setup

$(\mathsf{mpk}, \mathsf{msk})$

Alice

$\vec{y}$

$C = \mathsf{Enc}\,(\mathsf{mpk}, \vec{y})$

C →

Bob

$\vec{x}, \mathsf{sk}_{\vec{x}}$

$\langle \vec{x}, \vec{y} \rangle = \mathsf{Dec}(\mathsf{sk}_{\vec{x}}, C)$

$$\begin{aligned} F_x : \mathcal{R}^{\ell} &\mapsto \mathcal{R} \\ y &\mapsto \langle \vec{x}, \vec{y} \rangle \end{aligned}$$

Previous work

Schemes mod p do not recover large inner products or are inefficient.

PKC 2015	Crypto 2016	2016	PKC 2017
[ABDP15]	[ALS16]	[ABCP16]	[BBL17]
First IPFE schemes, from LWE and DDH, only selectively secure.	Full security, from LWE, DDH and DCR.	Full security, less efficient than [ALS16].	Generic constructions from HPS.

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First IPFE schemes, from LWE and DDH, only selectively secure.	Full security, from LWE, DDH and DCR.	Full security, less efficient than [ALS16].	Generic constructions from HPS.	IPFE mod p adaptive security no restriction on size and efficient!

Framework

Framework (sketch) [CL15]

Group with an easy discrete logarithm (DL) subgroup

- $G = \langle g \rangle$ cyclic group of order $p \cdot s$ such that $\gcd(p, s) = 1$.
- p large prime
- s unknown
- $F = \langle f \rangle$ subgroup of G of order p.
- $G^p = \langle g_p \rangle = \{x^p, x \in G\}$ subgroup of G of order s,

$$G = F \times G^p.$$

- DL is **easy** in F (DL: given f and $h = f^x$, find $x \in \mathbf{Z}/p\mathbf{Z}$)

New Assumption

Hard Subgroup Membership problem HSM:

Hard to distinguish p-th powers in G

$$\{x \xleftarrow{\$} G\} \approx_c \{x \xleftarrow{\$} G^p\}.$$

Analogy to Paillier's cryptosystem

Paillier's framework

- Message space $\mathbf{Z}/N\mathbf{Z}$ with N RSA modulus
- Relies on Paillier's DCR assumption
  - e.g. distinguishing N^{th} powers in $\mathbf{Z}/N^2\mathbf{Z}$

Our framework

- Messages encoded in $\mathbf{Z}/p\mathbf{Z}$ with p prime
  - Size of p **independent** of security parameter
- Relies on HSM assumption
  - e.g. distinguishing p^{th} powers in G of order $p \cdot s$
- **Instantiation:** class groups of an imaginary quadratic field [CL15]

Sampling exponents

Problem

s unknown, so orders of G^p and G unknown

$\Rightarrow$ Cannot sample uniformly from G or G^p!

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Solution

Use upper bound $\tilde{s}$ of s to instantiate distributions $\mathcal{D}$ and $\mathcal{D}_p$ s.t.

$$\{g^x, x \hookleftarrow \mathcal{D}\} \approx \mathcal{U}(G) \text{ and } \{g_p^x, x \hookleftarrow \mathcal{D}_p\} \approx \mathcal{U}(G^p)$$

In practice: Folded gaussian distributions with large standard deviation

$\Rightarrow$ better efficiency (shorter exponents) than folded uniforms

Inner Product Functional Encryption mod p from HSM

IPFE scheme mod p from HSM (simplified)

Setup For $i = 1, \ldots, \ell$ do $t_i \hookleftarrow \mathcal{D}$ and $h_i = g_p^{t_i}$

$$\mathsf{msk} = \vec{t} \text{ and } \mathsf{mpk} = (h_1, \ldots, h_\ell)$$

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Enc **Plaintext:** $\vec{y} = (y_1, \ldots, y_\ell) \in (\mathbf{Z}/p\mathbf{Z})^\ell$

Sample $r \hookleftarrow \mathcal{D}_p$

Ciphertext:

$$\vec{C} = (C_0 = g_p^r, C_1 = f^{y_1} \cdot h_1^r, \ldots, C_\ell = f^{y_\ell} \cdot h_\ell^r)$$

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Dec From $\vec{C}, \vec{x}$ and $\mathsf{sk}_{\vec{x}}$:

$$\langle \vec{x}, \vec{y} \rangle \bmod p$$

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Such that:

$$\prod_{i=1}^{\ell} C_i^{x_i} / C_0^{\mathsf{sk}_{\vec{x}}} = f^{\langle \vec{x}, \vec{y} \rangle} \xrightarrow{\text{DL}} \langle \vec{x}, \vec{y} \rangle \bmod p$$

Security

This scheme is secure under the HSM assumption.

Proof overview – inspired by [ALS16]

$$\vec{C} = (C_0 = g_p^r, C_1 = f^{y_{b*,1}} \cdot h_1^r, \ldots, C_\ell = f^{y_{b*,\ell}} \cdot h_\ell^r)$$

- Game 0 original security game

Proof overview – inspired by [ALS16]

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- Game 0 original security game
- Game 1 use **secret key** to compute challenge ciphertext [CS02]
- Game 2 indistinguishable from Game 1 under the HSM assumption.

In Game 2, from $\mathcal{A}$'s view b^* is **statistically hidden**, given

- the public key
- the challenge ciphertext
- key derivation queries

Information fixed by public key

$$\mathsf{mpk} = \{h_i = g_p^{t_i \bmod s}\}_{i \in [\ell]}$$

$$\Big\downarrow \text{ Fixes}$$

$$(t_1, \ldots, t_\ell) \bmod s$$

$(t_1, \ldots, t_\ell) \bmod p$ is still **uniformly** distributed to $\mathcal{A}$.

Information fixed by challenge ciphertext

$$\vec{C}^* = (C_0 = g_p^r \cdot f^u, \{C_i = f^{y_{b^*,i}} \cdot {C_0}^{t_i}\}_{i \in [\ell]})$$

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For $i = 1 \ldots, \ell$

$$C_i = g_p^{r \cdot t_i \mod s} \cdot f^{y_{b^*,i} + u \cdot t_i \mod p}$$

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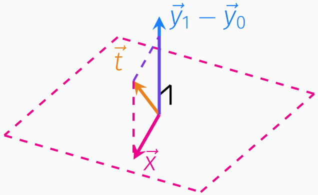
$$\vec{y}_{b*,i} + u \cdot t_i \mod p$$

Information fixed by key derivation oracle

Because of restriction on secret key queries,
all queries $\vec{x}$ satisfy $\langle \vec{x}, \vec{y}_0 \rangle = \langle \vec{x}, \vec{y}_1 \rangle \mod p$

$\downarrow$



$\forall\, \vec{x}$ s.t. $\langle \vec{x}, \vec{y}_0 - \vec{y}_1 \rangle = 0 \mod p$,
$\mathcal{A}$ can learn $\mathsf{sk}_{\vec{x}} = \langle \vec{t}, \vec{x} \rangle$

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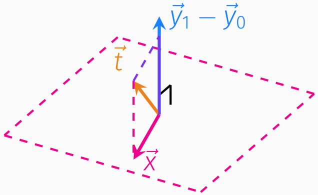

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↓

Remaining entropy on $\vec{t}$ contained in $\langle \vec{t}, \vec{y}_0 - \vec{y}_1 \rangle \mod p$

Information fixed by key derivation oracle

Given info from mpk and C^*, the distribution

$\mathcal{D}_0$ of $\vec{t}$ is over 1-dim lattice Λ_0 proportional to $\vec{y}_0 - \vec{y}_1$

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Reduce $\mathcal{D}_0$ mod sub-lattice $p\Lambda_0$ s.t. $\Lambda_0 / p\Lambda_0 \simeq (\vec{y}_0 - \vec{y}_1)\mathbf{Z}/p\mathbf{Z}$

↓

Choosing large enough standard deviation ensures

$\vec{t} \mod p$ follows a distribution $\approx \mathcal{U}(\Lambda_0 / p\Lambda_0)$ [GPV08]

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↓

$\langle \vec{t}, \vec{y}_0 - \vec{y}_1 \rangle \mod p$ follows a distribution $\approx \mathcal{U}(\mathbf{Z}/p\mathbf{Z})$

$\mathcal{A}$'s success probability

From $\mathcal{A}$'s view, $\langle \vec{t}, \vec{y}_0 - \vec{y}_1 \rangle \mod p$ follows a distribution $\approx \mathcal{U}(\mathbf{Z}/p\mathbf{Z})$.

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The information on b^* is contained in:

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$\mathcal{A}$ cannot guess b^* with proba $> 1/2 + \text{negl}$

Conclusion

- Many **details** hidden in this talk (stateful KeyDer)
- IPFE from weaker assumption DDH-f
- Instantiation using **class groups** of an imaginary quadratic field
  - Best known algorithms for underlying problems in $L(1/2)$
  - Shorter keys!
- **Efficiency** comparison for 128-bit security, $\ell = 100$
  - Enc $\approx$ 0.7s; Dec $\approx$ 1.9s **vs.** 0.8s and 9.6s in [ALS16]
  - $sk_{\vec{x}}$ of 13852 bits **vs.** 313344 bits in [ALS16]
  - Dependency in ℓ is linear
- **Ongoing work**
  - CCA secure schemes
  - Applying framework to other cryptographic primitives

Questions?

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