

# Efficient Laconic Cryptography from Learning With Errors

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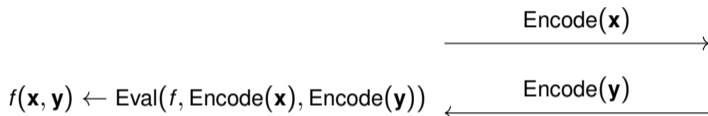
## (Round-Optimal) Two-Party Computation (2PC)

**Alice (“Receiver”)**

$\mathcal{A}(f, \mathbf{x} \in \{0, 1\}^*)$

**Bob (“Sender”)**

$\mathcal{B}(f, \mathbf{y} \in \{0, 1\}^*)$



† Alice and Bob have some function  $f : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{0, 1\}^*$ .

† Alice has input  $\mathbf{x} \in \{0, 1\}^*$ , Bob has input  $\mathbf{y} \in \{0, 1\}^*$ .

† After the 2PC,

‡ Alice should learn (i.e. “receive”)  $f(\mathbf{x}, \mathbf{y})$ , but nothing else about  $\mathbf{y}$ , and

‡ Bob should know nothing about  $\mathbf{x}$ .

† In general, Alice and Bob could each represent a member of a large group.

## Secure Delegation: “Alice-Optimised” 2PC

Let  $FHE = FHE.(KGen, Enc, Dec, Eval)$  be a fully homomorphic encryption scheme.

**Alice (“Receiver”)**

$\mathcal{A}(f, \mathbf{x} \in \{0, 1\}^*)$

$(pk, sk) \leftarrow FHE.KGen(1^\lambda)$

$ctxt_{\mathbf{x}} \leftarrow FHE.Enc(pk, \mathbf{x})$

$f(\mathbf{x}, \mathbf{y}) \leftarrow FHE.Dec(sk, ctxt_{f(\mathbf{x}, \mathbf{y})})$

**Bob (“Sender”)**

$\mathcal{B}(f, \mathbf{y} \in \{0, 1\}^*)$

$f_{\mathbf{y}}(\cdot) := f(\cdot, \mathbf{y})$

$ctxt_{f(\mathbf{x}, \mathbf{y})} \leftarrow FHE.Eval(pk, f_{\mathbf{y}}, ctxt_{\mathbf{x}})$

$\xrightarrow{pk, ctxt_{\mathbf{x}}}$

$\xleftarrow{ctxt_{f(\mathbf{x}, \mathbf{y})}}$

† Let  $|\cdot|$  denote description size.

† Alice’s work:  $|\mathbf{x}| \ll |f| + |\mathbf{y}|$ , i.e. “Alice-optimised”.

† Bob’s work:  $|f| + |\mathbf{y}| \gg |\mathbf{x}|$ .

† Can be done “efficiently” (say, atomic ops in ms) from standard lattice-based assumptions.

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## Laconic Cryptography or “Reverse Delegation”: “Bob-Optimised” 2PC

An emerging paradigm with numerous theoretical results [CDG+17; QWW18; DGI+19; DGGM19]

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Encode( $\mathbf{x}$ )



Encode( $\mathbf{y}$ )



$$f(\mathbf{x}, \mathbf{y}) \leftarrow \text{Eval}(f, \text{Encode}(\mathbf{x}), \text{Encode}(\mathbf{y}))$$

We want:

† Bob’s work:  $|\mathbf{y}| \lll |\mathbf{f}| + |\mathbf{x}|$ , i.e. “Bob-optimised”.

† Alice’s work:  $|\mathbf{f}| + |\mathbf{x}| \ggg |\mathbf{y}|$ .

Why is it challenging?

† Bob does not even have time to read  $f$  or  $\mathbf{x}$  in full.

† Encode( $\mathbf{y}$ ) needs to be just enough for Alice to unpack  $f(\mathbf{x}, \mathbf{y})$ .

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## Applications to Non-Laconic Cryptography

(The techniques used for) laconic cryptography had led to:

- † **Identity-based encryption (IBE)** from weaker assumptions [DG17b; DG17a; DGHM18; BLSV18]
- † Two-round **multiparty computation (MPC)** from minimal assumptions [GS17; GS18c; BL18]
- † Adaptively secure **garbled circuits** from weaker assumptions [GS18b]
- † **Trapdoor functions** from weaker assumptions [GH18]
- † Simpler **indistinguishability obfuscation (iO)** for Turing machines [GS18a]
- † Single-server **private-information retrieval (PIR)** from weaker assumptions [DGI+19]

## Laconic Cryptography Examples and “Non-Blackbox Barrier”

| Primitive   | $\mathbf{x}$  | $\mathbf{y}$                                   | $f(\mathbf{x}, \mathbf{y})$   |
|---|---|--|---|
| L. Oblivious Transfer<br>[CDG+17]   | Big database<br>$D \in \{0, 1\}^n$  | Index $i \in [n]$ ,<br>messages $\mu_0, \mu_1$ | $\mu_0$ if $D[i] = 0$ ;<br>$\mu_1$ if $D[i] = 1$                      |
| L. Priv. Set Intersection<br>[ABD+21; ALOS22]                                       | Big set $A$   | Small set $B$                                  | $A \cap B$  |
| L. Function Evaluation<br>[QWW18]   | Function $g$  | Input $\mathbf{y}$                             | $g(\mathbf{y})$   |
| Reg.-based Encryption<br>[GHMR18; GHM+19; GV20]<br><b>L. Encryption (this work)</b> | $(\text{sk}_{\text{id}^\dagger}, (\text{id}, \text{pk}_{\text{id}})_{\text{id} \in R})$ | Identity $\text{id}^*$ ,<br>message $\mu$      | $\mu$ if $\text{id}^\dagger = \text{id}^* \in R$<br>$\perp$ otherwise |

Before this work, all of the above requires “non-blackbox” techniques,  
 e.g. homomorphically evaluate a circuit implementing a public-key encryption  
 $\implies$  Completely impractical



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## Our Results

- † Introduce “laconic encryption” (LE) as central building block of laconic cryptography  
LE = RBE without stringent update efficiency requirements
- † Algebraic construction of LE from learning with errors (LWE) w/ poly. modulus-to-noise ratio
- † Blackbox transformations  $LE \rightarrow LOT, LPSI, \text{ and } RBE$
- † Open-source implementation of LE (first of anything laconic):  
For database with at most  $2^{50}$  identities, 10ms encrypt/decrypt time
- † By-product: Identity-based encryption (IBE) w/ unbounded ID space and tight reduction from LWE

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## Laconic Encryption in a Nutshell

† Implicit in existing LOT constructions

† For simplicity, consider static array of public keys  $(pk_1, \dots, pk_n)$   
(actual construction allows dynamic and efficient updates)

**Alice (“Receiver”)**

$\mathcal{A}(sk_{id}, pk_1, \dots, pk_n)$

$digest \leftarrow Hash(pk_1, \dots, pk_n)$

$wit_{id} \leftarrow \text{Witness of “}pk_{id} \in digest\text{”}$

$\underbrace{\mu \leftarrow LE.Dec(sk_{id}, wit_{id}, ctxt_{id,\mu})}_{\text{Time} \ll n}$

**Bob (“Sender”)**

$\mathcal{B}(id, \mu)$

digest

Pseudorandom (hiding both  $id$  and  $\mu$ ) without  $sk_{id}$

$ctxt_{id,\mu}$

$ctxt_{id,\mu} \leftarrow LE.Enc(digest, id, \mu)$

Time  $\ll n$

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## Our Approach

### Natural Construction Idea

- † Pick favourite public-key encryption scheme
- † Design “encryption-friendly” hash function
- † Encrypt w.r.t. the statement “ $pk_{id} \in \text{digest}$ ”, so that can decrypt with  $(sk_{id}, wit_{id})$

### Concrete Instantiation

- † In Dual-Regev encryption [GPV08],  $pp = \mathbf{B}$ ,  $pk = \mathbf{y}$ ,  $sk = \mathbf{x}$  short vector satisfying

$$\mathbf{B} \cdot \mathbf{x} = \mathbf{y} \pmod{q} \quad \text{and} \quad \|\mathbf{x}\| \ll q \quad \text{i.e. short integer solution (SIS) relation}$$

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## Dual-Regev Encryption [GPV08]

- † Public parameters:  $pp = \mathbf{B}$  wide uniformly random matrix
- † Public key:  $pk = \mathbf{y}$  vector
- † Secret key:  $sk = \mathbf{x}$  *short* vector satisfying  $\mathbf{B} \cdot \mathbf{x} = \mathbf{y} \bmod q$  and  $\|\mathbf{x}\| \ll q$
- † Encryption of  $\mu$ :  $ctxt = (c_0, c_1)$  where

$$\mathbf{c}_0^\top = \mathbf{s}^\top \cdot \mathbf{B} + \text{noise} \bmod q \quad \text{and} \quad c_1 = \mathbf{s}^\top \cdot \mathbf{y} + \text{Encode}(\mu) + \text{noise} \bmod q$$

for random LWE secret  $\mathbf{s}$

- † Decryption: Recover  $\mu$  by decoding

$$\begin{aligned} c_1 - \mathbf{c}_0^\top \cdot \mathbf{x} &= \mathbf{s}^\top \cdot (\mathbf{y} - \mathbf{B} \cdot \mathbf{x}) + \text{Encode}(\mu) + \text{noise} \bmod q \\ &= \text{Encode}(\mu) + \text{noise} \bmod q \end{aligned}$$

- † Pseudorandom ciphertext from LWE assumption, i.e.  $((\mathbf{B} \mid \mathbf{y}), \mathbf{s}^\top \cdot (\mathbf{B} \mid \mathbf{y}) + \text{noise}) \approx \text{uniform}$
- † Take home message: Allows encrypting w.r.t. a short integer solution (SIS) relation  $(\mathbf{B}, \mathbf{y})$

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- † Secret key:  $sk = \mathbf{x}$  *short* vector satisfying  $\mathbf{B} \cdot \mathbf{x} = \mathbf{y} \bmod q$  and  $\|\mathbf{x}\| \ll q$
- † Encryption of  $\mu$ :  $ctxt = (\mathbf{c}_0, c_1)$  where

$$\mathbf{c}_0^\top = \mathbf{s}^\top \cdot \mathbf{B} + \text{noise} \bmod q \quad \text{and} \quad c_1 = \mathbf{s}^\top \cdot \mathbf{y} + \text{Encode}(\mu) + \text{noise} \bmod q$$

for random LWE secret  $\mathbf{s}$

- † Decryption: Recover  $\mu$  by decoding

$$\begin{aligned} c_1 - \mathbf{c}_0^\top \cdot \mathbf{x} &= \mathbf{s}^\top \cdot (\mathbf{y} - \mathbf{B} \cdot \mathbf{x}) + \text{Encode}(\mu) + \text{noise} \bmod q \\ &= \text{Encode}(\mu) + \text{noise} \bmod q \end{aligned}$$

- † Pseudorandom ciphertext from LWE assumption, i.e.  $((\mathbf{B} \mid \mathbf{y}), \mathbf{s}^\top \cdot (\mathbf{B} \mid \mathbf{y}) + \text{noise}) \approx \text{uniform}$
- † Take home message: Allows encrypting w.r.t. a short integer solution (SIS) relation  $(\mathbf{B}, \mathbf{y})$

## Dual-Regev Encryption [GPV08]

- † Public parameters:  $pp = \mathbf{B}$  wide uniformly random matrix
- † Public key:  $pk = \mathbf{y}$  vector
- † Secret key:  $sk = \mathbf{x}$  *short* vector satisfying  $\mathbf{B} \cdot \mathbf{x} = \mathbf{y} \bmod q$  and  $\|\mathbf{x}\| \ll q$
- † Encryption of  $\mu$ :  $ctxt = (\mathbf{c}_0, c_1)$  where

$$\mathbf{c}_0^\top = \mathbf{s}^\top \cdot \mathbf{B} + \text{noise} \bmod q \quad \text{and} \quad c_1 = \mathbf{s}^\top \cdot \mathbf{y} + \text{Encode}(\mu) + \text{noise} \bmod q$$

for random LWE secret  $\mathbf{s}$

- † Decryption: Recover  $\mu$  by decoding

$$\begin{aligned} c_1 - \mathbf{c}_0^\top \cdot \mathbf{x} &= \mathbf{s}^\top \cdot (\mathbf{y} - \mathbf{B} \cdot \mathbf{x}) + \text{Encode}(\mu) + \text{noise} \bmod q \\ &= \text{Encode}(\mu) + \text{noise} \bmod q \end{aligned}$$

- † Pseudorandom ciphertext from LWE assumption, i.e.  $((\mathbf{B} \mid \mathbf{y}), \mathbf{s}^\top \cdot (\mathbf{B} \mid \mathbf{y}) + \text{noise}) \approx \text{uniform}$
- † Take home message: Allows encrypting w.r.t. a short integer solution (SIS) relation  $(\mathbf{B}, \mathbf{y})$

## Gadget Matrix and Binary Decomposition

Recall “gadget matrix”  $\mathbf{G}$  [MP12]

$$\mathbf{G} = \begin{pmatrix} 1 & 2 & \dots & 2^{\lceil \log q \rceil - 1} & & & & & \\ & & & & \ddots & & & & \\ & & & & & & & & \\ & & & & & & 1 & 2 & \dots & 2^{\lceil \log q \rceil - 1} \end{pmatrix}$$

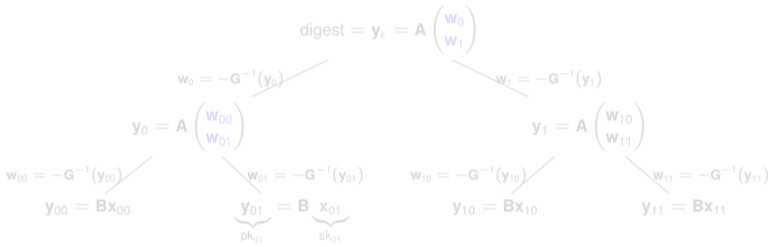
and let  $\mathbf{G}^{-1}$  denote the “binary-decomposition operator”.

For any  $q$ -ary vector  $\mathbf{v}$  as tall as  $\mathbf{G}$ , we have

$$\mathbf{G} \cdot \mathbf{G}^{-1}(\mathbf{v}) = \mathbf{v}.$$

# Encryption-Friendly Hash Function

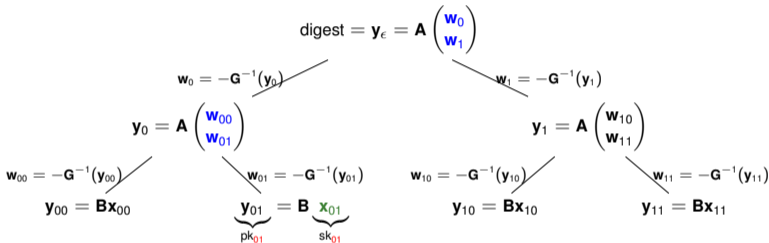
$$\text{Hash}(\mathbf{v}_0, \mathbf{v}_1) := \mathbf{A}_0 \cdot (-\mathbf{G}^{-1}(\mathbf{v}_0)) + \mathbf{A}_1 \cdot (-\mathbf{G}^{-1}(\mathbf{v}_1)) = \mathbf{A} \cdot \begin{pmatrix} -\mathbf{G}^{-1}(\mathbf{v}_0) \\ -\mathbf{G}^{-1}(\mathbf{v}_1) \end{pmatrix} \text{ mod } q$$



$$\underbrace{\begin{pmatrix} \mathbf{A}_0 & \mathbf{A}_1 & & & \\ \mathbf{G} & & \mathbf{A}_0 & \mathbf{A}_1 & \\ & & & \mathbf{G} & \mathbf{B} \end{pmatrix}}_{\mathbf{B}_{\text{Hash},01}} \begin{pmatrix} w_0 \\ w_1 \\ w_{00} \\ w_{01} \\ x_{01} \end{pmatrix} = \underbrace{\begin{pmatrix} y_\epsilon \\ 0 \\ 0 \end{pmatrix}}_{\mathbf{y}_{\text{digest}}} \text{ mod } q$$

# Encryption-Friendly Hash Function

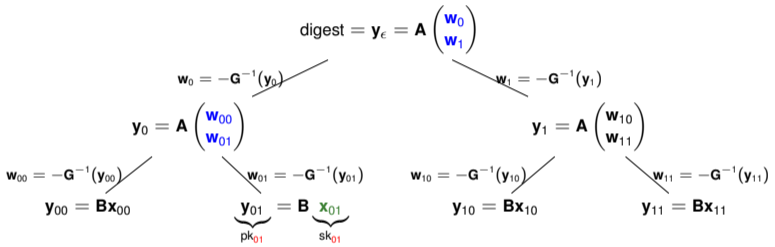
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$$\underbrace{\begin{pmatrix} \mathbf{A}_0 & \mathbf{A}_1 & & & & \\ \mathbf{G} & & \mathbf{A}_0 & \mathbf{A}_1 & & \\ & & & \mathbf{G} & \mathbf{B} & \end{pmatrix}}_{\mathbf{B}_{\text{Hash},01}} \begin{pmatrix} w_0 \\ w_1 \\ w_{00} \\ w_{01} \\ x_{01} \end{pmatrix} = \underbrace{\begin{pmatrix} y_\epsilon \\ 0 \\ 0 \end{pmatrix}}_{\mathbf{y}_{\text{digest}}} \text{ mod } q$$

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## Putting Everything Together

- † User id has public key  $pk_{id} = \mathbf{y}_{id}$  and secret key  $sk_{id} = \mathbf{x}_{id}$
- † Digest  $\text{digest} = \mathbf{y}_\epsilon = \text{Merkle-tree hash of } (pk_{id}) = (\mathbf{y}_{id})_{id}$
- † Witness  $wit_{id} = \text{concatenation of all } \mathbf{w}'\text{s along the root-to-id path and their siblings, e.g.}$

$$wit_{01}^T = (\mathbf{w}_0^T, \mathbf{w}_1^T, \mathbf{w}_{00}^T, \mathbf{w}_{01}^T)$$

- † To encrypt  $\mu$  to  $id \in \{0, 1\}^\ell$ , use Dual-Regev to encrypt w.r.t.  $(\mathbf{B}_{\text{Hash},id}, \mathbf{y}_{\text{digest}})$  where

$$\mathbf{B}_{\text{Hash},id} = \begin{pmatrix} \mathbf{A}_0 & \mathbf{A}_1 & & & & & & & & \\ \bar{id}_1 \mathbf{G} & id_1 \mathbf{G} & \mathbf{A}_0 & \mathbf{A}_1 & & & & & & \\ & & \bar{id}_2 \mathbf{G} & id_2 \mathbf{G} & \ddots & \ddots & & & & \\ & & & & \ddots & \ddots & \mathbf{A}_0 & \mathbf{A}_1 & & \\ & & & & & & \bar{id}_\ell \mathbf{G} & id_\ell \mathbf{G} & \mathbf{B} & \end{pmatrix} \text{ and } \mathbf{y}_{\text{digest}} = \begin{pmatrix} \mathbf{y}_\epsilon \\ \mathbf{0} \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \end{pmatrix}$$

- † Decrypt using  $(wit_{id}^T, \mathbf{x}_{id})$  as Dual-Regev secret key, where  $\mathbf{B}_{\text{Hash},id} \cdot \begin{pmatrix} wit_{id} \\ \mathbf{x}_{id} \end{pmatrix} = \mathbf{y}_{\text{digest}} \pmod{q}$

## Key Points in Security Proof

† We cannot use security of Dual-Regev directly:

$(\mathbf{B}_{\text{Hash}, \text{id}}, \mathbf{y}_{\text{digest}})$  is not a properly distributed Dual-Regev public key.

† Instead, we need to argue layer-by-layer about pseudorandomness of LWE samples w.r.t.

$$(\mathbf{B}_{\text{Hash}, \text{id}}, \mathbf{y}_{\text{digest}}) = \begin{pmatrix} \mathbf{A}_0 & \mathbf{A}_1 & & & & & & & \mathbf{y}_\epsilon \\ \bar{\text{id}}_1 \mathbf{G} & \text{id}_1 \mathbf{G} & \mathbf{A}_0 & \mathbf{A}_1 & & & & & \mathbf{0} \\ & & \bar{\text{id}}_2 \mathbf{G} & \text{id}_2 \mathbf{G} & \ddots & \ddots & & & \vdots \\ & & & & \ddots & \ddots & & & \vdots \\ & & & & & & \mathbf{A}_0 & \mathbf{A}_1 & \mathbf{0} \\ & & & & & & \bar{\text{id}}_\ell \mathbf{G} & \text{id}_\ell \mathbf{G} & \mathbf{B} & \mathbf{0} \end{pmatrix}.$$

† Somewhere in the proof, we need to perform noise flooding/drowning/smudging/etc., i.e. show that

$$\{\text{Linearly-correlated LWE samples}\} \approx \{\text{Short linear combinations of LWE samples + fresh noise}\}$$

Traditionally, this is either done by

‡ using super-polynomial-size modulus  $\implies$  require LWE w/ super-polynomial modulus-to-noise ratio, or

‡ arguing about Rényi divergence  $\implies$  incur polynomial reduction loss.

We instead show a tight reduction from LWE w/ polynomial modulus-to-noise ratio.

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We instead show a tight reduction from LWE w/ polynomial modulus-to-noise ratio.

## Conclusion

- † Algebraic construction of laconic encryption (LE) from standard LWE
- † Blackbox transformations  $LE \rightarrow LOT, LPSI, \text{ and } RBE$
- † Open-source implementation of LE:
  - For database with at most  $2^{50}$  identities, 10ms encrypt/decrypt time
- † By-product: Identity-based encryption (IBE) w/ unbounded ID space and tight reduction from LWE

Code



[https://github.com/ahmadrezarahimi/  
laconic-encryption](https://github.com/ahmadrezarahimi/laconic-encryption)

Paper



<https://ia.cr/2023/404>

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