Middle-Product Learning with Rounding Problem and its Applications

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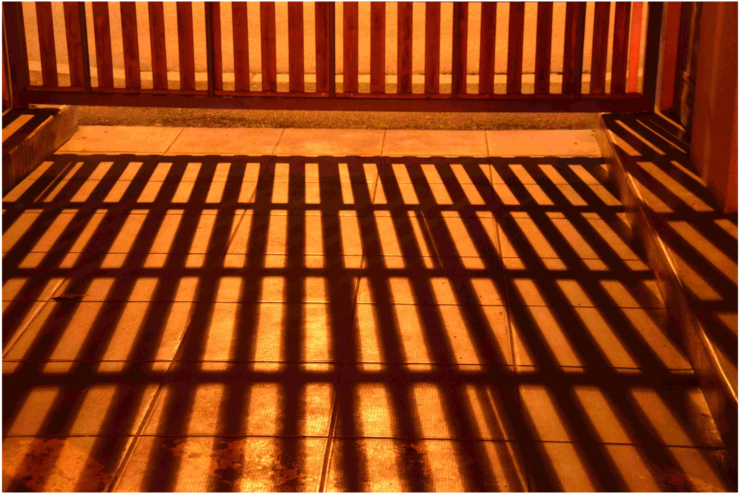
Dromadaire, 23th January 2020, Rennes, France

Preview

We define a Learning with Errors (LWE) variant which

- is at least as hard as **exponentially many** P-LWE instances,
- is **deterministic** and
- can be used to build **efficient** public key encryption.

Introduction



Lattice-Based Cryptography

Definition (Informal)

Cryptographic constructions whose security are based on the hardness of lattice problems

Advantages

- **post-quantum**
- **efficient** constructions
- **advanced** cryptographic constructions
- worst-case to average-case **security** reductions

Definition (Informal)

Cryptographic constructions whose security are based on the hardness of lattice problems

Advantages and Motivation

- **post-quantum** ?
- **efficient** constructions often only asymptotically
- **advanced** cryptographic constructions
- worst-case to average-case **security** reductions

  not for all variants used in practice

Euclidean Lattices

An **Euclidean Lattice** Λ of **dimension** n is the set of linear combinations with integer coefficients of n independent basis vectors $B = (\vec{b}_1, \ldots, \vec{b}_n)$ in the real vector space $\mathbb{R}^n$,

$$\Lambda(B) = \left\{ \sum_{i=1}^{n} a_i \cdot \vec{b}_i \mid a_i \in \mathbb{Z} \right\}.$$

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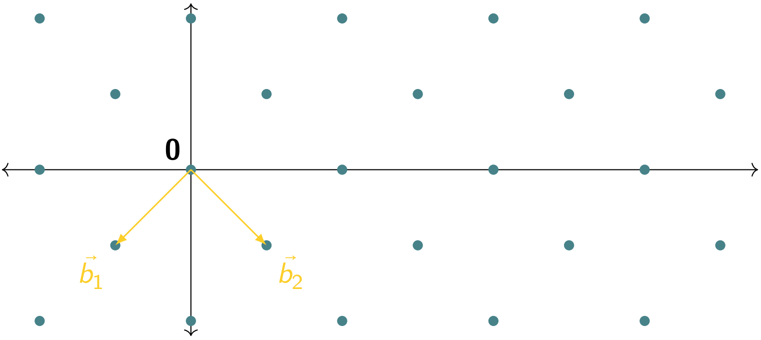

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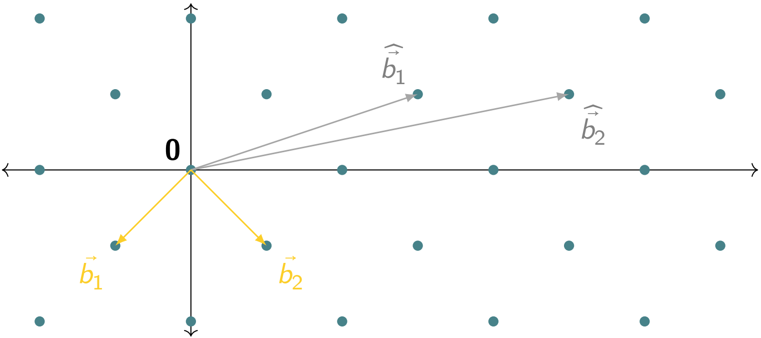

Hard lattice problems SVP and SVP_γ

Let $\Lambda(B)$ be a lattice of dimension n with basis B.
Its **minimum** is defined as $\lambda_1(\Lambda(B)) = \min_{\vec{v} \in \Lambda(B) \setminus \{\vec{0}\}} \|\vec{v}\|$.[1]

[1] Fix any norm, e.g. Euclidean norm $\|\cdot\|_2$

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Problem (Shortest Vector Problem)

Given a basis B, find $\vec{v} \in \Lambda(B)$ non-zero such that $\|\vec{v}\| = \lambda_1(\Lambda(B))$.

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The complexity of SVP$_\gamma$ increases with n, but decreases with γ.

It is believed to be exponential in n for any polynomial γ.

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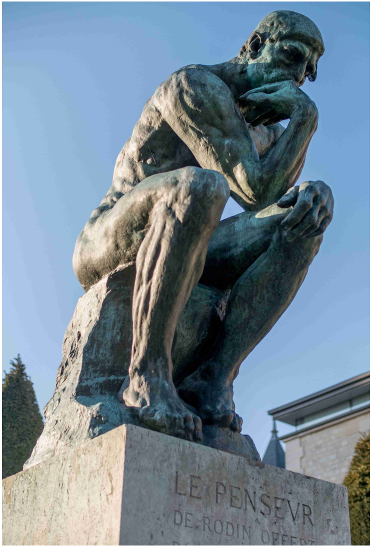
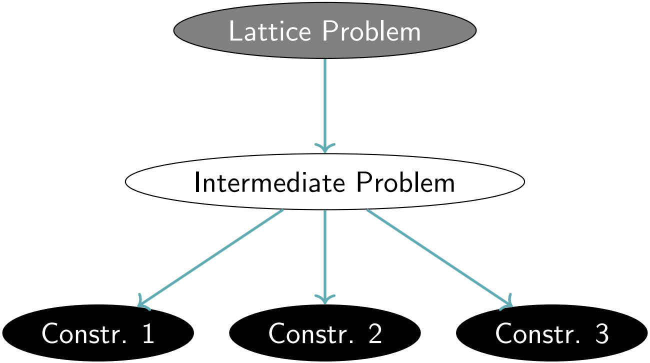
What to do with it?



Images: wikipedia.fr

Intro

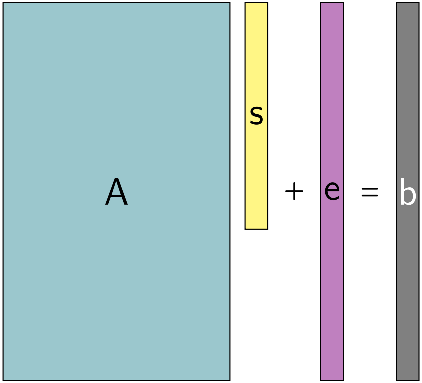


Lattice Problem
Intermediate Problem
Constr. 1
Constr. 2
Constr. 3

Intermediate Problem: Learning With Errors (LWE)

Given A $\in \mathbb{Z}_q^{m\times n}$ and b $\in \mathbb{Z}_q^{m}$.

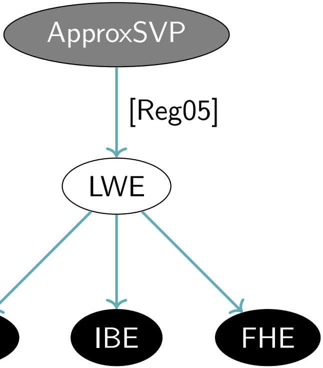
Search: Find s $\in \mathbb{Z}_q^{n}$ and a small noise e (e.g. Gaussian) s.t.:



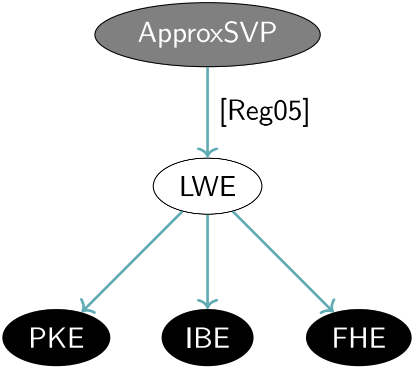
Decision: Distinguish from uniform distribution

Problem: Need to store $m(n+1)\log q$ bits for A and b.

Intro

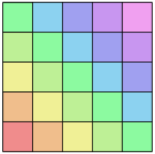


PKE=Public Key Encryption, IBE=Identity-Based Encryption,
FHE=Fully Homomorphic Encryption



Advantage:		security based on **all** Euclidean lattices
Disadvantages:	(1)	large public keys
	(2)	Gaussian sampling

Idea: Give A a **structure**, need to store less.



Structured LWE: Polynomial Learning With Errors

Algebraic setting: Replace $\mathbb{Z}_q^n$ by $R_q = \mathbb{Z}_q[x]/\langle f(x)\rangle$, for example $f(x) = x^n + 1$

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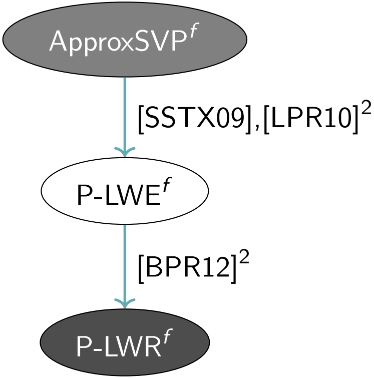
Given $a = \sum_{i=0}^{n-1} a_i x^i \in R_q$ and $b \in R_q$.

Search: Find $s \in R_q$ and small noise e such that:

$$\underbrace{\begin{pmatrix} a_0 & -a_{n-1} & \cdots & -a_1 \\ a_1 & & & \\ \vdots & & \ddots & \vdots \\ a_{n-1} & & \cdots & a_0 \end{pmatrix}}_{\mathrm{Rot}_f(\mathrm{a})} \cdot \mathrm{s} + \mathrm{e} = \mathrm{b}$$

This corresponds to $a \cdot s + e = b$ in R_q.

Two ideas: structured and deterministic variants



[2] For simplicity, take the power-of-two cyclotomic case, where P-LWE and R-LWE (resp. P-LWR and R-LWR) coincide.

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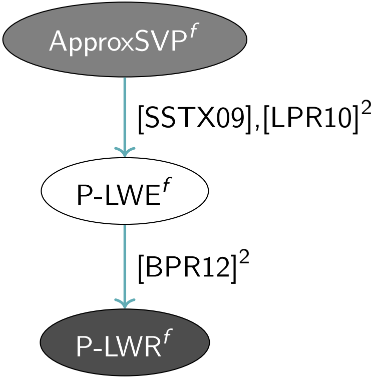

Disadvantages: (1) security based on **restricted** class of lattices, **depending** on f

(2) **decisional** P-LWR: super-polynomial modulus

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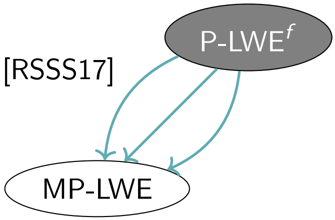
Previous work:



Solution: (1) Middle-Product LWE
reduction for **exponentially** many f

[3] We simplified the graph, their reduction was shown for the ring variants.

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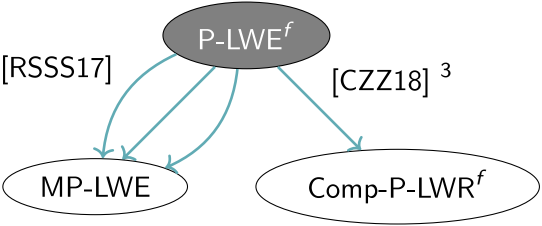

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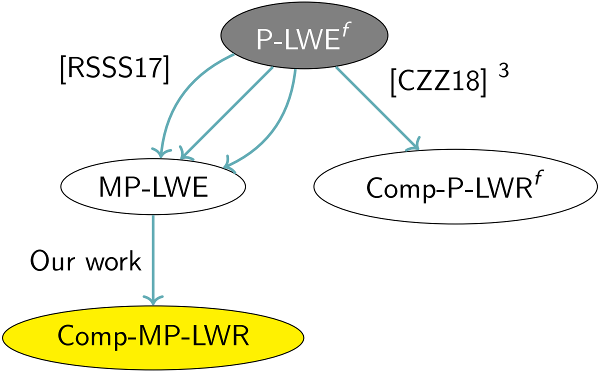

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Contributions

We define:

(1) Computational Middle-Product Learning with Rounding Problem (Comp-MP-LWR)

We show:

(2) Efficient reduction from MP-LWE to Comp-MP-LWR

We construct:

(3) Public Key Encryption based on Comp-MP-LWR

Computational Middle-Product Learning with Rounding

Middle-Product

Given polynomials $a = \sum_{i=0}^{n-1} a_i x^i \in \mathbb{Z}^{<n}[x]$, $b = \sum_{i=0}^{2n-2} b_i x^i \in \mathbb{Z}^{<2n-1}[x]$.

Their product is

$$\begin{aligned} a \cdot b = c_0 + \cdots + c_{n-2}x^{n-2} \\ + \mathbf{c_{n-1}}x^{n-1} + \mathbf{c_n}x^n + \cdots + \mathbf{c_{2n-2}}x^{2n-2} \\ + c_{2n-1}x^{2n-1} + \cdots + c_{3n-3}x^{3n-3} \in \mathbb{Z}^{<3n-2}[x]. \end{aligned}$$

Their **middle-product** is

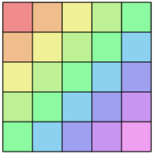
$$a \odot_n b = \mathbf{c_{n-1}} + \mathbf{c_n}x + \cdots + \mathbf{c_{2n-2}}x^{n-1} \in \mathbb{Z}^{<n}[x].$$

Matrix representation of the middle-product

Given a polynomial $b = \sum_{i=0}^{2n-2} b_i x^i \in \mathbb{Z}^{<2n-1}[x]$.

Its **Hankel matrix** is

$$\text{Hankel}(b) = \begin{pmatrix} b_0 & b_1 & \dots & b_{n-1} \\ b_1 & b_2 & \dots & b_n \\ & & \iddots & \\ b_{n-1} & b_n & \dots & b_{2n-2} \end{pmatrix} \in \mathbb{Z}^{n \times n}.$$



For any $a \in \mathbb{Z}^{<n}[x]$ it yields

$$a \odot_n b = \text{Hankel}(b) \cdot \overline{\mathbf{a}},$$

where $\overline{\mathbf{a}} = (a_{n-1}, \dots, a_0)^T$.

Image: wikipedia.de

Middle-Product LWE + LWR

Let χ be a distribution on $\mathbb{R}^{<n}[x]$ (e.g., Gaussian)

Definition ($\text{MP-LWE}_{q,n,\chi}$ distribution for $s \in \mathbb{Z}_q^{<2n-1}[x]$)

Sample $a \leftarrow U\left(\mathbb{Z}_q^{<n}[x]\right)$ and $e \leftarrow \chi$.

Return $(a, b = a \odot_n s + e) \in \mathbb{Z}_q^{<n}[x] \times \mathbb{R}_q^{<n}[x]$

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Given $p < q$ and $y \in \mathbb{Z}_q$. Rounding $\lfloor y \rceil_p = \left\lfloor \frac{p}{q} \cdot y \right\rceil \bmod p$.

Definition (MP-LWR$_{p,q,n}$ distribution for $s \in \mathbb{Z}_q^{<2n-1}[x]$)

Sample $a \leftarrow U\left(\mathbb{Z}_q^{<n}[x]\right)$.

Return $(a, \lfloor b \rceil_p = \lfloor a \odot_n s \rceil_p) \in \mathbb{Z}_q^{<n}[x] \times \mathbb{R}_p^{<n}[x]$

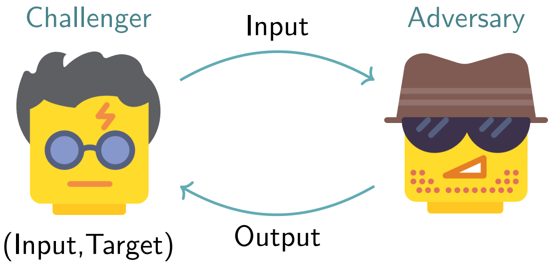
Intuition

Challenger

Adversary

Images: flaticon.com

Intuition



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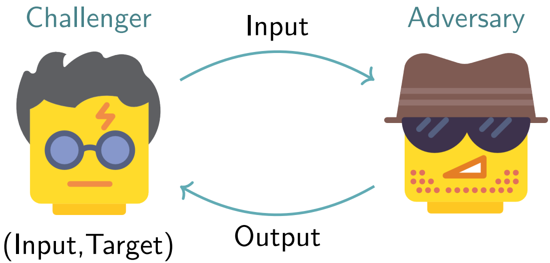

Output=Target?

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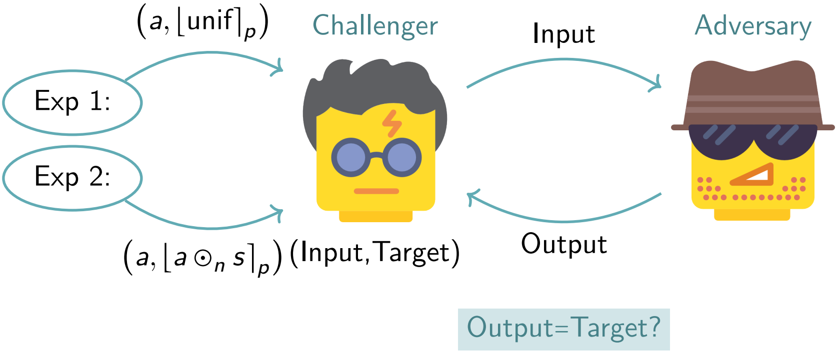

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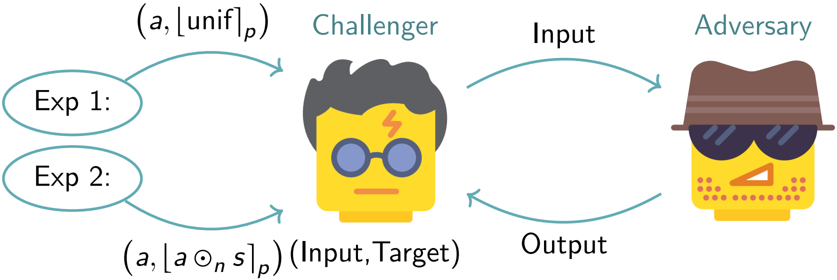


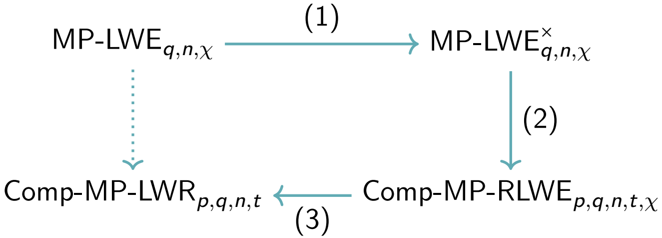
Output=Target?

Assumption (Comp-MP-LWR)

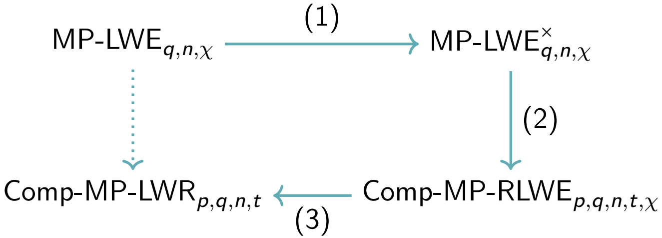
The adversary can't obtain more information from the MP-LWR distribution than from the rounded uniform distribution.

Images: flaticon.com

Reduction

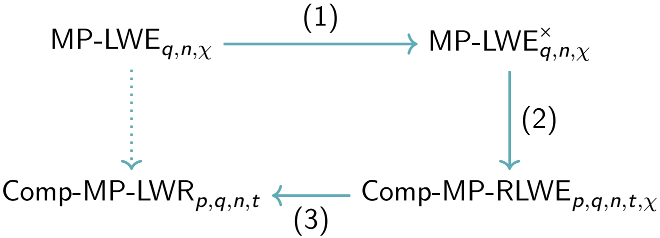

MP-LWE$_{q,n,\chi}$
(1)
MP-LWE$^{\times}_{q,n,\chi}$
(2)
Comp-MP-RLWE$_{p,q,n,t,\chi}$
(3)
Comp-MP-LWR$_{p,q,n,t}$

Reduction



(1) If secret s with **full-rank** Hankel matrix:
(e.g., for q prime, happens with probability $\geq 1 - 1/q$)
a uniform $\Rightarrow$ $a \odot_n s = \text{Hankel}(s) \cdot \overline{\mathbf{a}}$ uniform

Reduction



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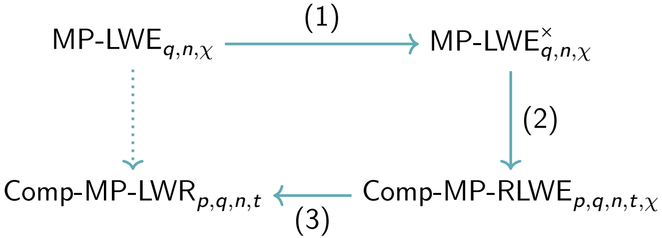
Reduction



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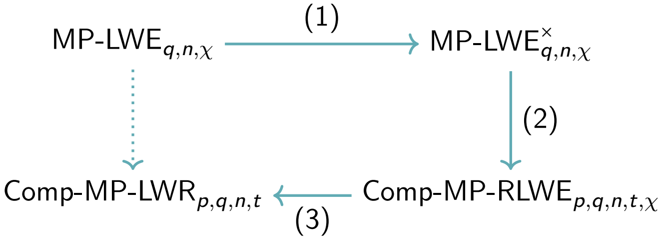
(3) Using Rényi divergence:
fix number of samples t **a priori**

Reduction



The reduction is **dimension-preserving** and works for **polynomial-sized** modulus q.
Elements sampled from χ are bounded by B with probability at least δ, s.t.

$$q > 2pBnt \text{ and } \delta \geq 1 - \frac{1}{tn}.$$

PKE based on Comp-MP-LWR

Public Key Encryption from Comp-MP-LWR

High level: Adapt encryption scheme from [CZZ18] to middle-product setting.

Public Key Encryption from Comp-MP-LWR

Message $\mu \in \{0,1\}^{n/2}$ and random oracle $H\colon \{0,1\}^{n/2} \to \{0,1\}^{n/2}$

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KeyGen(1^λ). Sample $s \leftarrow U\left(\mathbb{Z}_q^{<2n-1}[x]\right)$ s.t. $\mathrm{rank}(\mathrm{Hankel}(s)) = n$ and $a_i \leftarrow U\left(\mathbb{Z}_q^{<n}[x]\right)$ for $1 \le i \le t$.

$$\mathbf{pk} = \left(a_i, b_i = \lfloor a_i \odot_n s \rceil_p\right)_{i \le t} \text{ and } \mathbf{sk} = s.$$

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Enc(μ, pk). Sample $r_i \leftarrow U\left(\{0,1\}^{<n/2+1}[x]\right)$ for $1 \le i \le t$. Set

$$c_1 = \sum_{i \le t} r_i a_i \quad \text{and} \quad v = \sum_{i \le t} r_i \odot_{n/2} b_i.$$

Further set $c_2 = \langle v \rangle_2$ and $c_3 = H(\lfloor v \rceil_2) \oplus \mu$.

Public Key Encryption from Comp-MP-LWR

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Dec(c_1, c_2, c_3, sk). Compute $w = c_1 \odot_{n/2} s$ and return $\mu' = c_3 \oplus H(\mathrm{REC}(w, c_2))$.

Correctness

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For **correctness**, reconciliation mechanism has to work:

$$\mathrm{REC}(w, \langle v \rangle_2) = \lfloor v \rceil_2 \text{ if } |w - v| < \frac{q}{8}$$

IND-CPA Security

pk $= (a_i, b_i)$, **sk** $= s$ and ciphertext $c = (c_1, c_2, c_3)$, where

$$c_1 = \sum r_i a_i, \quad v = \sum r_i \odot_{n/2} b_i, \quad c_2 = \langle v \rangle_2 \quad \text{and}$$

$$c_3 = H(\lfloor v \rceil_2) \oplus \mu.$$

Sequence of steps:

- Distinguishing advantage of IND-CPA game upper bounded by advantage of computing preimage $\lfloor v \rceil_2$ of H,

IND-CPA Security

pk $= \left(a_i, \$ \right)$, **sk** $= s$ and ciphertext $c = (c_1, c_2, c_3)$, where

$$c_1 = \sum r_i a_i, \quad v = \sum r_i \odot_{n/2} \$, \quad c_2 = \langle v \rangle_2 \quad \text{and}$$

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- Replace v by uniform sample, thus c_2 is also uniform (use Generalized LHL),
- As c_1 and c_2 are independent, adversary can only **guess** preimage of H.

Parameter Choice 1/2

Let λ be the security parameter and $c > 0$ be a positive constant.

Parameter	[RSSS17]	Our work
n	$\geq \lambda$	$\geq \lambda$
t	$\Theta(\log n)$	$\Theta(\log n)$
q	$\Theta(n^{2.5+c}\sqrt{\log n})$	$\Theta(n^{4+c}\log^2 n)$
$\log q$	$\Theta(\log n)$	$\Theta(\log n)$
α	$\Theta\left(\frac{1}{n\sqrt{\log n}}\right)$	-
p	-	$\Theta(n \log n)$
B	-	$O(n^{2+c})$

Figure: Comparison of asymptotic parameters

$\Rightarrow$ scheme is **correct** and **secure**,

$\Rightarrow$ **asymptotically**, key and ciphertext size dominated by $\log q$.

$\Rightarrow$ increase of q due to restrictions in hardness proof and correctness

Parameter Choice 2/2

Let $n \geq \lambda$ and let t be the number of samples.

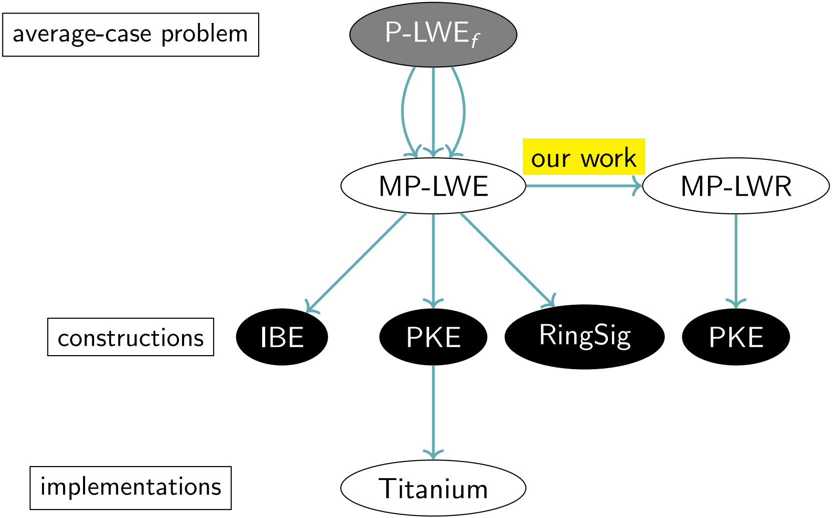
Parameter	[RSSS17]	Our work
$\log q$	$\Theta(\log n)$	$\Theta(\log n)$
Key size		
sk pk	$(2n-1)\cdot\log q$ $t\cdot(2n\log q)$	$(2n-1)\cdot\log q$ $t\cdot(n\log q + n\log p)$
Ciphertext size		
c_1 c_2 c_3	$(3/2n)\log q$ $n/2\log q$ -	$(3/2n)\log q$ $n/2$ $n/2$

Figure: Comparison of key and ciphertext sizes

Concrete Security

- In **practice**: derive parameters from the best known attacks (e.g. BKZ with quantum sieving)
- Primal and dual attack on public key/ciphertext
- Using Toeplitz-matrix representation to define the underlying lattice (ignore sparse structure)
- Recently, Sakzad, Steinfeld and Zhao improve the crypto-analysis [SSZ19]

Big Picture Middle-Product



Open Questions

- Reduction from **decisional** MP-LWE to **decisional** MP-LWR[4],
- Alternatively: **search-to-decision** reduction for MP-LWR,
- PKE based on MP-LWR in the **standard model**,
- Using **small** secret to gain in **efficiency**.

[4] Carries over to other structured LWR variants.

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Thank you

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