On the Learning Parity with Noise Problem

Luca Melis

Università degli Studi di Firenze

Århus Universitet

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Advisors:
Prof. Alessandro Piva
Prof. Fabrizio Argenti

Co-advisors:
Dr. Claudio Orlandi
Prof. Ivan Damgård

Scenario

Cryptography schemes

- address the security of communication across an insecure medium
- are usually based only on complexity assumptions (standard model)

Near Future:

- Problem: What if someone constructs large quantum computers?
- Cryptography world may fall apart:
  1. cryptographic assumptions broken by efficient quantum algorithms e.g. *factoring and discrete-logarithm broken by Shor's algorithm*
  2. proofs of security (or *reduction*) become unuseful

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Post-Quantum cryptography

Schemes that are believed to resist classical & quantum computers

- **Code-based cryptography**
- **Lattice-based cryptography**

Our contribution

- We investigate about the Learning Parity with Noise (LPN) problem
- We propose a Threshold Public-Key Encryption scheme based on LPN
- We propose a Commitment protocol based on LPN

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Learning Parity with Noise Problem LPN

- Dimension ℓ (security parameter), $q \gg \ell$, $\tau \in \left(0, \frac{1}{2}\right)$
- **Search**: find $\boldsymbol{s} \in \mathbb{Z}_2^\ell$ given "noisy random inner products"

Errors $e_i \leftarrow \mathrm{Ber}_\tau$, i.e. $\Pr(e_i = 1) = \tau$

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Decision: <u>distinguish</u> (A, b) from uniform (A, b)

decisional and search LPN are "polynomially equivalent"

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Learning Parity with Noise Problem LPN

Hardness of LPN

The best known attacks against search LPN problem takes

- $2^{\Theta(\ell/\log \ell)}$ having the same number of samples q
- $2^{\Theta(\ell/\log\log \ell)}$ having $q = poly(\ell)$ samples
- $2^{\Theta(\ell)}$ having $q = \Theta(\ell)$ samples

where ℓ is the security parameter

Interesting features

- Efficiency → suitable for limited computing power devices (e.g. RFID)
- quantum algorithm resistance

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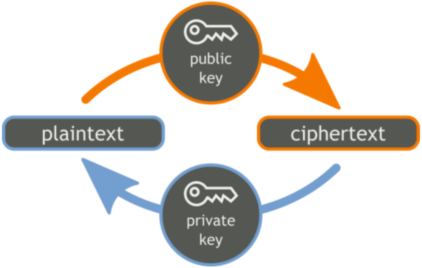

Public-key cryptography

- the ability of decrypting or signing is restricted to the owner of the secret key.
- $\Rightarrow$ only one person has all the power

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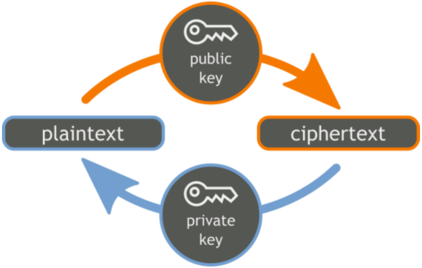

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Threshold Public-Key Encryption schemes

Solution: Threshold PKE

- The secret key is split into shares and each share is given to a group of users.
- users can decrypt or sign only if enough, a *threshold*, cooperate

Our contribution

A Threshold Public-Key Encryption scheme which is:

- based on LPN
- secure in the *Semi-honest model*

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Alekhnovich PKE scheme

Key Generation

The receiver $\mathtt{R}$ chooses

- a secret key $\boldsymbol{s} \xleftarrow{R} \mathbb{Z}_2^{\ell}$
- $\boldsymbol{A} \xleftarrow{R} \mathbb{Z}_2^{q\times\ell}$ and the error $\boldsymbol{e} \leftarrow \mathrm{Ber}_\tau^q$, where $\tau \in \Theta(\frac{1}{\sqrt{\ell}})$ and computes the pk as $(\boldsymbol{A}, \boldsymbol{b} = \boldsymbol{A}\boldsymbol{s} \oplus \boldsymbol{e})$

Encryption of a message bit $m \in \mathbb{Z}_2$

Sender $\underline{\mathtt{S}}$		Receiver $\underline{\mathtt{R}}$
choose a vector $\boldsymbol{f} \leftarrow \mathrm{Ber}_\tau^q$		
compute $\boldsymbol{u} = \boldsymbol{f} \cdot \boldsymbol{A}$		
$c = \langle \boldsymbol{f}, \boldsymbol{b} \rangle \oplus m$	$\xrightarrow{(\boldsymbol{u}, c)}$	

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The receiver $\mathtt{R}$ computes $d = c \oplus \langle \boldsymbol{s}, \boldsymbol{u} \rangle = \cdots = \langle \boldsymbol{f}, \boldsymbol{e} \rangle \oplus m$

ThPKE: Protocol phases

- **Key Generation**
- **Key Assembly**
- **Encryption**
- **Partial Decryption**
- **Finish Decryption**

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Key Generation

- All the receivers share a matrix $\boldsymbol{A} \xleftarrow{R} \mathbb{Z}_2^{q \times \ell}$
- Each receiver $\mathtt{R_i}$ indipendently choose a secret key $\boldsymbol{s}_i \xleftarrow{R} \mathbb{Z}_2^{\ell}$ and an error $\boldsymbol{e}_i \leftarrow \mathrm{Ber}_\tau^q$
- the public key for $\mathtt{R_i}$ is the pair $(\boldsymbol{A}, \boldsymbol{b}_i = \boldsymbol{A}\boldsymbol{s}_i \oplus \boldsymbol{e}_i)$

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Key Assembly

The combined public key is the pair $(\boldsymbol{A}, \boldsymbol{b})$, where

$$\boldsymbol{b} = \bigoplus_{i \in I} \boldsymbol{b}_i$$

and I is the users subset

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Sender $\underline{\mathtt{S}}$ Receivers $\underline{\mathtt{R_i}, \mathtt{R_j}}$

$$(\boldsymbol{C_1}, \boldsymbol{c_2}) \leftarrow \texttt{ThLPN.Enc}(m, \boldsymbol{b})$$

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Encryption function (Alekhnovich scheme)

$$\boldsymbol{C_1} = \boldsymbol{F} \cdot \boldsymbol{A},\ \boldsymbol{c_2} = \boldsymbol{F} \cdot \boldsymbol{b} \oplus \underbrace{\begin{bmatrix} 1 \\ \dots \\ 1 \end{bmatrix}}_{q} \cdot m \qquad \text{where } \boldsymbol{F} := \begin{bmatrix} \boldsymbol{f_1} \\ \dots \\ \boldsymbol{f_q} \end{bmatrix}, \boldsymbol{f_i} \leftarrow \mathrm{Ber}_{\tau}^{q}$$

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Receiver $\underline{\mathtt{R_i}}$ Receiver $\underline{\mathtt{R_j}}$

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Finish decryption

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- the bit in the vector $\boldsymbol{d}$ that is in majority is separately chosen by each receiver as the plaintext m

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Protocol Security Analysis

Semi-honest model

A semi-honest party:

1. Follows the protocol properly
2. Keeps a record of all its intermediate computations

Security

- **Encryption:** from the Alekhnovich's scheme security
- **Decryption:** from the LPN hardness assumption, as each P_i is generating LPN samples

$$d_i = C_1 \cdot s_i \oplus \nu_i$$

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- **Decryption:** from the LPN hardness assumption, as each $\mathtt{R}_i$ is generating LPN samples

$$\boldsymbol{d_i} = \boldsymbol{C_1} \cdot \boldsymbol{s_i} \oplus \boldsymbol{\nu_i}$$

Protocol Security Analysis

Relaxed Semi-honest model

- Semi-honest model not so realistic (*replay attacks* may occur)
- Problem: if the same message is encrypted multiple times then it is possible to recover information about the secret key from the ciphertexts

Proposed solutions

1. implement the receivers as stateful machines (not good in resource-constrained devices)
2. make use of [illegible] (i.e. deterministic algorithms that simulate truly random functions, given a "seed")

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Conclusions and Open Problems

Our contribution

- study the security of our Threshold Public-Key Encryption scheme in the *malicious model*

LPN open problems

- relation between standard LPN and some variants
- Does LPN with noise rate τ imply anything about LPN with $\tau' < \tau$? Is there a threshold?
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Commitment Protocols

Scenario:

Alice wants to keep a message secret from Bob for now but she intends to reveal it to Bob at some time in the future

Commitment protocol

- Alice commits the message and Bob does not learn any information about it (hiding property)
- Alice choose to open the commitment and reveal the message, but she cannot change the value committed (property)

Our contribution

We presented a Commitment protocol

- based on the commitment protocol by *Jain et al*
- based on Exact-LPN problem (where $wt(e) = \lfloor \tau \cdot \ell \rceil$)
- does not need a trusted third party

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The commitment protocol by *Jain et al*

Setup Phase

In order to commit a message $\boldsymbol{m} \in \mathbb{Z}_2^k$ where $k \in \Theta(\ell + v)$
We state $\boldsymbol{A} = [\boldsymbol{A'} \| \boldsymbol{A''}] \in \mathbb{Z}_2^{k \times (\ell+v)}$ as the common reference string (CRS).
Finally, we set $w = \lfloor \tau k \rceil$.

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define $\boldsymbol{d} = (\boldsymbol{m'}, \boldsymbol{r'})$ $\xrightarrow{\quad \boldsymbol{d} \quad}$

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Opening phase

define $\boldsymbol{d} = (\boldsymbol{m'}, \boldsymbol{r'})$ $\xrightarrow{\quad \boldsymbol{d} \quad}$

computes $\boldsymbol{e'} = \boldsymbol{c} \oplus \boldsymbol{A}\left(\boldsymbol{r'}\|\boldsymbol{m'}\right)$

$\xleftarrow{\quad Yes, No \quad}$ accepts iff $\boldsymbol{wt}(\boldsymbol{e'}) = w$

Proposed commitment protocol

Problem

We need a trusted third party for the common matrix $\boldsymbol{A} = [\boldsymbol{A}' \| \boldsymbol{A}'']$

Solution:

The Commitment and Opening phases are the same as in the original scheme

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$$
\begin{array}{ccc}
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\text{chooses } \boldsymbol{A}' \xleftarrow{R} \mathbb{Z}_2^{k \times \ell} & \xrightarrow{\quad \boldsymbol{A}' \quad} &
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The Commitment and Opening phases are the same as in the original scheme

The commitment protocol: a LPN-based variant

LPN variant

- security directly based on the standard LPN problem
- **Commit phase:** we set $w' = 2 \cdot \lfloor \tau k \rceil$ and we choose $\boldsymbol{e}$ such that $\boldsymbol{wt}(\boldsymbol{e}) \leq w'$

Choice of parameters

According to

Levieil, Éric and Fouque, Pierre-Alain
An Improved LPN Algorithm
Springer Berlin Heidelberg, 2006

we choose $\ell = 768$ and noise rate $\tau = \frac{1}{8} \Rightarrow 2^{90}$ bytes of memory to solve LPN

Theorem

Our commitment scheme is statistically binding and computationally hiding

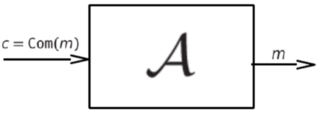
Proof

Statistically binding

even if S is computationally unbounded she cannot cheat with probability greater than 2^{-k}

Computationally hiding

- proof for reduction (single bit message)
- we assume that $\mathcal{A}$ is able to break the commitment scheme



- Let $\mathcal{B}$ an oracle

images/oracle

where $\boldsymbol{b} = \begin{cases} \text{random} & w.p.\ 1/2 \\ \boldsymbol{A's} \oplus \boldsymbol{e} & w.p.\ 1/2 \end{cases}$

Proof

images/proof$_0$

Proof

images/proof$_1$

Proof

images/proof$_2$

Proof

images/proof$_3$

Proof

images/proof$_4$

case 1)

$\boldsymbol{b}$ is random $\Rightarrow \boldsymbol{c} = \boldsymbol{b} \oplus \boldsymbol{A''} m$ is a onetime-pad encryption

$\Rightarrow \mathcal{A}$ guesses w.p. $\frac{1}{2}$

Proof

images/proof$_5$

case 2)

$\boldsymbol{b}$ is a Exact-LPN sample $\Rightarrow$ $\boldsymbol{c}$ is a well formed commitment
$\Rightarrow \mathcal{A}$ guesses w.p. 1 (by hypothesis)

Proof

images/proof$_3$

case 1) and 2)

Let E = the reduction breaks the Exact-LPN problem,

Proof

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Let E = the reduction breaks the Exact-LPN problem,

$$\Pr(E) = \Pr\left(E \middle|\ \boldsymbol{b} = \boldsymbol{A'}\boldsymbol{s} \oplus \boldsymbol{e}\right) \cdot \Pr\left(\boldsymbol{b} = \boldsymbol{A'}\boldsymbol{s} \oplus \boldsymbol{e}\right) + \Pr\left(E \middle|\ \boldsymbol{b} \text{ is random}\right) \cdot \Pr\left(\boldsymbol{b} \text{ is random}\right)$$

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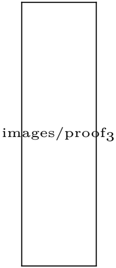

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Exact-LPN hardness $\Rightarrow$ Hiding commitment