About Homomorphic Encryption
Implementation Progresses and Challenges

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Outline

1. Context and Introduction

2. Applications and Practical Issues
   - Security
   - How to express high-level algorithms?
   - Huge expansion of ciphertexts
   - Complexity

3. Conclusion
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1. **Context and Introduction**
2. **Applications and Practical Issues**
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3. **Conclusion**
Fully Homomorphic Encryption

Usual encryption: SSL (Internet), Credit Cards, ...

Fully Homomorphic Encryption [FHE]: Since 2009, we know how to evaluate polynomials (= Boolean circuits = programs) on encrypted data (since 1978 we only knew how to add OR to multiply, not both).
Homomorphic Encryption: we are dreaming of . . .

A revolution: data and/or services outsourcing without losing confidentiality!
Impact: citizens, administrations, companies, military, . . .
Domains: health care, power plants, multimedia content delivery, . . .
Computations: comparing, sorting/filtering, clustering, compressing, . . .
Program’s output = Circuit Eval = Polynomial Eval

\[ F_i(x) = x_i x_{i+8} \quad i = 1, \ldots, 7 \]
\[ F_0(x) = x_8(x_{16} + 1) \]
It has been a long quest to handle polynomials.
Lattice based S/FHE in a nutshell...
Lattice based S/FHE in a nutshell . . .

Ex : FHE over the integers \[\text{[vDGHV 10]}\]

- Secret key (symmetric version here) : \(s\)
- Encryption of \(m \in \{0, 1\} : \alpha, \beta\) random
  \[c = m + 2\alpha + \beta s\]
- Decryption : \(c \mod s = m + 2\alpha\)
  \[m = (c \mod s) \mod 2\]
Lattice based S/FHE in a nutshell . . .

Ex : FHE over the integers [vDGHV 10]

- Secret key (symmetric version here) : $s$
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  $$c = m + 2\alpha + \beta s$$
- Decryption : $c \mod s = m + 2\alpha$
  $$m = (c \mod s) \mod 2$$
- Homomorphic addition : $c + c' = m + m' + 2(\alpha + \alpha') + (\beta + \beta')s$
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To ensure a coherent decryption, we need : $m + m' + 2(\alpha + \alpha') < s$
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**Condition :**

To ensure a coherent decryption, we need:

\[ m + m' + 2(\alpha + \alpha') < s \]

If $2\alpha < s/2$, $2\alpha' < s/2$, and if $c$ and $c'$ are fresh ciphertexts, then it is ok.
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If $c_i$ is not a fresh ciphertext, we might not be able to decrypt it properly (too much noise)! 
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If $c_i$ is not a fresh ciphertext, we might not be able to decrypt it properly (too much noise)!
And it is even worse in the case of homomorphic multiplication!

The challenge is to keep control of this noise during computation.
How to handle this noise? (1/2)

- **FHE**: $\times$ unbounded $\rightarrow$ using bootstrapping
  - once the setting is fixed, "any" circuit can be evaluated
  - 2009-2014: too complex to be used in practice
  - **BUT** recent improvements, e.g. [PV15] to optimize bootstrapping use, [CGGI16] to accelerate it
How to handle this noise? (2/2)

- SHE schemes: $\times$ bounded $\rightarrow$ without bootstrapping
  - a limited (but often sufficient) number of multiplications
  - maximum mult. depth is related to the setting (cannot be modified afterwards)
  - a lower complexity
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PoC: Outsourcing of (medical) diagnosis

Simple threshold tests in cardiology diagnosis executed in the encrypted domain

Outsourced medical diagnosis
Some recent experimental results

Example of demonstration


- Setup:
  - Algorithm implementation, compilation and deployment on a server.
  - Homomorphic precalculation of Kreyvium keystream on the server.
  - The Android tablet sends the Kreyvium-encrypted private user health data.
  - The server receives and homomorphically « transcribes » to FHE.
  - The server homomorphically executes the diagnostic algorithm and sends back the encrypted answer to the tablet.
  - As the FHE secret key owner, the tablet is the only party able to decrypt and thus interpret the server reply.

- Characteristics:
  - Fan-Vercauteren sFHE.
  - Full-blown end-to-end 128 bits security.
  - 3.3 secs for program execution on the server.
  - < 4 secs RTD towards servers.

- Claim: practicality achieved for not-too-big-data realistic algorithms!
“Intelligent” and “Evolving” algorithms

IP concerns and software update for the service provider:

- Targeted advertising
- Access Control with respect to user profile
- Biometric authentication
- Medical Diagnosis
- Cloud-based biochemical reactor control
- Machine Learning (deep learning)
Want to play? (1/2)


2012: private implem. of [BGV12] dedicated to AES homo. eval. [GHS12]

2013-16: private platform at CEA [AFFGS13,FSFAG13],
home-made implem. of [BGV12] (vect and poly) and [FV12],
+ HElib and more recent open-source libraries

2013: open-source implementation of [vDGHV10] with the improvements from [CNT12]: https://github.com/coron/fhe

2013: private implementation in [CLT 13] dedicated to AES homomorphic evaluation using an improved version of [vDGHV10]

2013: private implementation of [BLLN 13], with good performances with 2 or 3 multiplicative depth
Want to play? (2/2)


2014: **open-source** implem. of [FV12] and [BLLN13] YASHE, compared in [LN14] [https://github.com/tlepoint/homomorphic-simon](https://github.com/tlepoint/homomorphic-simon)

2015: **open-source** library called SEAL1.0, based on YASHE [http://sealcrypto.codeplex.com/](http://sealcrypto.codeplex.com/)

2016: **open-source** library to efficiently handle polynomials, called NFLlib [https://github.com/quarkslab/NFLlib](https://github.com/quarkslab/NFLlib)

2016: **open-source** implementation of [FV12] based on NFLlib [https://github.com/CryptoExperts/FV-NFLlib](https://github.com/CryptoExperts/FV-NFLlib)

2016: **open-source** multi-precision moduli library, called HElib-MP [https://github.com/tricosset/HElib-MP](https://github.com/tricosset/HElib-MP), based on HElib

2016: SEAL1.0 is replaced by SEAL2.1, based on another implementation of [FV12] [http://sealcrypto.codeplex.com/](http://sealcrypto.codeplex.com/)

"soon": FV with RNS from [BEHZ16]; NFLlib based implementation of SHIELD [KGV15]; library related with [CGGI16]

also see common API [http://bristolcrypto.blogspot.jp/2017/02/homomorphic-encryption-api-software.html](http://bristolcrypto.blogspot.jp/2017/02/homomorphic-encryption-api-software.html) (work in progress)
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Semantic Security

Semantic security is necessary!
(and as S/FHE schemes are malleable, IND-CCA2 can never be achievable).

⇒ probabilistic encryption
Security

Which kind of security?

Semantic Security

Semantic security is necessary!
(and as S/FHE schemes are malleable, IND-CCA2 can never be achievable).

⇒ probabilistic encryption
⇒ expansion (ciphertexts are longer than plaintexts)
and parameters setting has a huge impact on expansion!
Semantic Security

Semantic security is necessary!
(and as S/FHE schemes are malleable, IND-CCA2 can never be achievable).

⇒ probabilistic encryption
⇒ expansion (ciphertexts are longer than plaintexts)
and parameters setting has a huge impact on expansion!

e.g. expansion is equal to (without batching):

- equal to 2 with Paillier cryptosystem (only +)
- around 5,000 with elliptic curve based solution [HF17] (+, × deg ≤ 4)
- between 500,000 and 1,000,000 for lattice-based S/FHE
Which security level?

**Security Analysis of elliptic curve based schemes**

Computational Security (w.r.t. DLP). Well understood and studied.

**Security Analysis of lattice based schemes**

Computational Security (w.r.t. hard problems as LWE, R-LWE,...)
Theoretical studies essentially focus on asymptotic and generic estimations (may be not so close to real S/FHE situations).
Some experiments (based on LLL, BKZ,...) provide estimations (but may remain too optimistic today).

See e.g. [Alb15, ABD16][Peik16][BF16][Alb17][AN17].
Which security level for lattice based S/FHE?

See the (online) estimator provided by Martin Albrecht (always evolving):

⇒ it is really hard today to know how to choose the right parameters to ensure a given security level (e.g. 128) and we really need more targeted attacks and studies to derive precise guidelines for the choice of parameters (see [MBF16] for a first attempt, based on the current state-of-the-art).
How to express high-level algorithms?

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How to express high-level algorithms?

**Applications: we are dreaming of . . .**

**A revolution**: data and/or services outsourcing without losing confidentiality!

**Impact**: citizens, administrations, companies, military, . . .

**Domains**: health care, power plants, multimedia content delivery, . . .

**Computations**: comparing, sorting/filtering, clustering, compressing, . . .
Our goal

To help programers (not crypto specialists!) to use S/FHE in the development of their software/hardware stuff [AFF+13][FAR+13][CS14]

1. Cryptographers are necessary to help choosing the most appropriate S/FHE scheme & data encoding & parameters:

   - Application
     - requirements
       - time constraints
       - space constraints
       - security constraints
     - FHE scheme & data encoding
     - parameters
     - several choices (and trade-offs)
     - real life
       - speed
       - memory
       - security level

2. This being done, programers must be able to go further alone, without interacting with cryptographers!
How to express high-level algorithms?

**With cryptographers : choosing data encoding (1/2)**

Your (sliced) data

Each piece of (sliced) data has to be related with one plaintext (a point of the lattice, *i.e.* integers or polynomials)
How to express high-level algorithms?

**With cryptographers : choosing data encoding (2/2)**

**Your data : managing bits or integers? (slicing)**

Processing integers may seem more interesting at a first glance, BUT in some cases using integers will reduce the set of algorithms one can execute in the encrypted domain, e.g. if-then-else implies a management at the bit-level.

In case we choose an encoding at the bit-level, we need to redefine integers encoding to get operators on integers (based on those on bits, with 2’s complement, sign bit, ...), for:

```
addition multiplication substraction << >>
```

**Batching (packing several plaintext into one)**

To process several bits (resp. integers) at the same time, e.g. using Chinese Remaining Theorem.
How to express high-level algorithms?

Programers are not obliged to impl. S/FHE

From Armadillo platform [AFF+13][FAR+13][CS14]:

Definition of C++ classes **ClearBit** and **CryptoBit** written with the help of cryptographers (link with data encoding and S/FHE scheme):

```
class C++ template<typename bit, int size>
```

Any programer can then use them:

**Example**

Applying a bubble sort on data in clear:
```
bsort<Integer<ClearBit,8> >(arr,n);
```

Applying the **same** bubble sort on encrypted data:
```
bsort<Integer<CryptoBit,8> >(arr,n);
```
How to express high-level algorithms?

Software Compilation Process and Optimization

- initial algorithm
- equivalent algorithm in C++ using ClearBit/CryptoBit templates
- equivalent Boolean circuit
- optimized Boolean circuit (especially with decreased multiplicative depth)
- C++ code for sequential or parallel execution

Choosing the right algorithm:
It is important to choose the algorithm with the best worst-case complexity (not usual!) if tests have to been performed over the encrypted data.
How to express high-level algorithms?

Software Compilation Process and Optimization

1. initial algorithm
   - code modification by the programmer

2. equivalent algorithm in C++ using ClearBit/CryptoBit templates
   - data slicing

3. equivalent Boolean circuit
   - optimization module

4. optimized Boolean circuit (especially with decreased multiplicative depth)

5. C++ code for sequential or parallel execution

C++ classes ClearBit and CryptoBit

Applying a bubble sort on data in clear:
\[ \text{bsort}\langle\text{Integer<ClearBit,8>}\rangle (arr,n); \]

Applying the same bubble sort on encr. data:
\[ \text{bsort}\langle\text{Integer<CryptoBit,8>}\rangle (arr,n); \]
Software Compilation Process and Optimization

How to express high-level algorithms?

1. **Initial Algorithm**
2. **Equivalent Algorithm in C++ using ClearBit/CryptoBit templates**
3. **Equivalent Boolean Circuit**
4. **Optimized Boolean Circuit (especially with decreased multiplicative depth)**
5. **C++ code for sequential or parallel execution**

**Code modification by the programmer**

**Data Slicing**

Going down at the Boolean level:
- Data slicing & conversion Pgm → Boolean circuit.
- Use XOR and AND for **ClearBit**
- Use HE-ADD and HE-MULT for **CryptoBit**
How to express high-level algorithms?

Program → Boolean circuit

Comparisons of Encrypted Data

How to perform tests and express if-then-else?

Boolean bitwise operators:

\[
\begin{align*}
    a < b & : \text{MSB of } a+(-b) \\
    a > b & : \text{MSB of } b+(-a) \\
    a = b & : (a < b) \text{ NOR } (a > b)
\end{align*}
\]

"if c then x = a else x = b" can be achieved through the following operator: 

\[
x = \text{select}(c,a,b) = \begin{cases} 
    a & \text{if } c=1 \\
    b & \text{otherwise}
\end{cases}
\]

\[
x = \text{select}(c,a,b) = (c \text{ AND } a) \text{ XOR } ((\text{NOT } c) \text{ AND } b)
\]

- no data leakage ;-) 
- BUT bit-level encoding + worst-case complexity as we have to evaluate the whole circuit (all the branches of the circuit)
How to express high-level algorithms?

**Bubble sort: a meaningful example**

**Classical bubble sort:**

```c
void bsort(int *arr, int n)
{
    for(int i=0; i<n-1; i++)
    {
        for(int j=1; j<n-i; j++)
        {
            if(arr[j-1] > arr[j])
            {
                int t = arr[j-1];
                arr[j-1] = arr[j];
                arr[j] = t;
            }
        }
    }
}
```

**Rewritten bubble sort:**

```c
void bsort(int *arr, int n)
{
    for(int i=0; i<n-1; i++)
    {
        for(int j=1; j<n-i; j++)
        {
            int gt = arr[j-1] > arr[j];
            int t = gt*arr[j-1]^(!gt*arr[j]);
            arr[j-1] = gt*arr[j]^(!gt*arr[j-1]);
            arr[j] = t;
        }
    }
}
```
How to express high-level algorithms?

Software Compilation Process and Optimization

1. Initial algorithm
2. Equivalent algorithm in C++ using ClearBit/CryptoBit templates
3. Equivalent Boolean circuit
4. Optimization module
5. Optimized Boolean circuit (especially with decreased multiplicative depth)
6. C++ code for sequential or parallel execution

**Optimization**

Minimization of the multiplicative length (also taking care of the width of the circuit and the total number of multiplications and additions).
Optimizing the Boolean circuit

Characterization of # add, # mul, × depth

Estimation and optimization possible with the help of **ClearBit**.

Some values for classical algorithms (before optimization):

<table>
<thead>
<tr>
<th></th>
<th>$\sum_{i=1}^{10} t[i]$ (4 bits)</th>
<th>threshold (4 bits)</th>
<th>$b^2 - 4ac$ (4 bits)</th>
<th>bubble sort (10x4 bits)</th>
<th>FFT (256x32 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td># add</td>
<td>99</td>
<td>390</td>
<td>126</td>
<td>2372</td>
<td>7291592</td>
</tr>
<tr>
<td># mul</td>
<td>27</td>
<td>60</td>
<td>32</td>
<td>238</td>
<td>5296128</td>
</tr>
<tr>
<td>× depth</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>69</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(16 bits)</td>
<td>(16 bits)</td>
<td>(10x8 bits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td># add</td>
<td>423</td>
<td>1188</td>
<td>3240</td>
<td></td>
<td></td>
</tr>
<tr>
<td># mul</td>
<td>279</td>
<td>1126</td>
<td>2790</td>
<td></td>
<td></td>
</tr>
<tr>
<td>× depth</td>
<td>16</td>
<td>32</td>
<td>136</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow$ **ClearBit** class helps to debug the implementation and to optimize it!
How to express high-level algorithms?

The trick: Program = Circuit = Polynomial

```cpp
#include <iostream>
#include <stdint.h>
#include "integer.h"

void f
    (std::istream &i,
     std::ostream &o)
{
    SlicedInteger<int8_t> a, b;
    i >> a >> b;
    b = b ^ 0x01;
    a &= b;
    o << a;
}
```

\[
F_i(x) = x_i x_{i+8} \quad i = 1, \ldots, 7
\]

\[
F_0(x) = x_8 (x_{16} + 1)
\]
Software Compilation Process and Optimization

How to express high-level algorithms?

1. Initial algorithm
2. Equivalent algorithm in C++ using ClearBit/CryptoBit templates
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Huge expansion of ciphertexts

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Huge expansion of ciphertexts

**An awful expansion factor!**

<table>
<thead>
<tr>
<th>Expansion (without batching)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current estimations of security parameters lead to an expansion factor</td>
</tr>
<tr>
<td>• equal to 2 with Paillier cryptosystem (only +)</td>
</tr>
<tr>
<td>• around 5,000 with elliptic curve based solution [HF17] $(+, \times deg \leq 4)$</td>
</tr>
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<td>• between 500,000 and 1,000,000 for lattice-based S/FHE</td>
</tr>
</tbody>
</table>

⇒ pb to store and process, and to transmit data encrypted with S/FHE!

1. it would be very nice to design new schemes with a lower expansion,
2. we can help by choosing a good data representation and pack several plaintexts together (batching: CRT, SIMD, RNS),
3. we also have to do our best to manage huge ciphertexts, e.g. properly combining classical symmetric encryption with S/FHE.
A revolution: data and/or services outsourcing without losing confidentiality!

Impact: citizens, administrations, companies, military, ...

Domains: health care, power plants, multimedia content delivery, ...

Computations: comparing, sorting/filtering, clustering, compressing, ...
How to efficiently upload S/FHE ciphertext?

Huge expansion of ciphertexts

Context and Introduction

Applications and Practical Issues

Conclusion

What kind of symmetric encryption is the most appropriate?
**HE-friendly ciphers? (1/2)**

**Main goal**

To **minimize the multiplicative depth** of the decryption function.

**First concrete proposals have been block ciphers**

- **Already existing block ciphers:**
  - Optimized implementations of AES [GHS12][CCKL+13][DHS14]
    → but AES’s × depth remains too large (→ too slow)
  - Lightweight block ciphers: SIMON [LN14], PRINCE [DSES14]
    → SIMON behaves better than AES
    → PRINCE behaves better than SIMON, but remains too slow

- **Dedicated block cipher:** Low-MC-80 and Low-MC-128 [ARSTZ15]
  → but subject to some interpolation attacks (sparse ANF)
  ⇒ a tweaked version has been presented at FSE 2016’s rump session (more rounds), but security remains not clear (≤ 118)
Huge expansion of ciphertexts

Ciphertext decompression with IV-based encryption

A new approach [CCF+16] to reduce the online phase to a minimum ...
Huge expansion of ciphertexts

Ciphertext decompression with IV-based encryption

... with an additive stream cipher ;-)

\[ k \rightarrow \text{HE}_{pk}(\cdot) \rightarrow \text{HE}_{pk}(k) \]

\[ \text{offline} \]

\[ m \rightarrow m \oplus \text{keystream} \rightarrow \text{HE}_{pk}(m) \]
HE-friendly ciphers? (2/2)

Using a stream cipher reduces on-line phase to the minimum. Current candidates for function $F$ are:

[CCCF+16] :

- Trivium: coming from eSTREAM (2008), firmly established security, 80 bits security
- Kreyvium: based on Trivium, same security confidence, 128 bits security

[MJSC 16] :

- Flip: lower complexity, but security should be more deeply analyzed [DLR 16]

According to today’s state-of-the-art, Kreyvium seems to be the best available solution (but may be replaced by Flip if new security analysis is good).
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High computation complexity related to the noise management.

**Cryptographic issues:**
⇒ it should be nice to have less complex S/FHE schemes, even if a huge effort has still been done and complexity already decreased a lot, and to optimize the use of bootstrapping, modulus switching, re-linearization, etc (e.g. see [PV15] for bootstrapping opt.).

**Application related issues:**
⇒ for a given target, we need to carefully choose the right algorithm (with the best worst-case complexity!)
⇒ we need to optimize the implementation (circuit optimization, bits/integers & batching, software/hardware implementation).
Some recent experimental results


- Setup:
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  - Homomorphic precalculation of Kreyvium keystream on the server.
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Conclusion

Nice

Very nice applications + post-quantum encryption :-)  
A lot of efforts and progresses (everything is moving really fast).  
Quite a lot of implementations available now.

Making small applications affordable! We are on the right way :-)  

BUT still a lot of (theoretical and practical) work to be done:

- **security** (to be better understood)
- **expansion** (to be better decreased and managed)
- **complexity** (worst-case complexity, bootstrapping optimization, etc)
- implementation **optimization** (Boolean circuit, software & hardware)
- help programmers to choose the right **scheme** with an adapted **setting** (and do not forget "classical" crypto solutions)
How to choose the right solution and implementation?

Several implementations have been publicly released, BUT they are often tested separately :-(

There are very few attempts of comparisons based on public implementations: [LN14] + more recent experiments to be published in the next weeks/months (couldn’t finish before this talk :-()
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Why is it difficult to FAIRLY compare schemes?

Security: it is difficult today to precisely link parameters setting with a given security level (hence difficult to be sure to compare the same security level for several schemes).

Expansion: batching has been proposed for some schemes, not all.

Complexity: we should compare implementations with the same optimization level.

Data encoding: some schemes work on bits/integers/polynomials.
How to choose the right solution and implementation?

Hence, choosing among lattice based schemes like BGV, FV, SHIELD, or even more classical schemes like BGN or BGN2 based on elliptic curves is not easy.
How to choose the right solution and implementation?

Hence, choosing among lattice based schemes like BGV, FV, SHIELD, or even more classical schemes like BGN or BGN2 based on elliptic curves is not easy.

And even for a given scheme, implementations may use

- different lattice structures,
- different noise generation strategy,
- different optimization level,
- different batching techniques.

Ex : FV from SEAL 2.1 and from FV-NFLlib are very different!

⇒ Hence we should provide very precise benchmarks to be fair.
French activities:
- design (S/FHE + friendly symmetric)
- security analysis
- batching
- compilation: software, hardware
- benchmarking and parameters setting

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WIFS 2017
The IEEE Workshop on Information Forensics and Security

Topics of interest include, but are not limited to:

- **Forensics**: Multimedia forensics | Counter Forensics | Acquisition Device Identification| Evidence Validation | Benchmarking
- **Biometrics**: Single or Multi-Modalities Systems | Security and Privacy | Spoofing | Performance Evaluation
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