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CONCRETE: Concrete Operates on Ciphertexts Rapidly by Extending TFHE

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ABSTRACT

Fully homomorphic encryption (FHE) extends traditional encryption schemes. It allows one to directly compute on encrypted data without requiring access to the decryption key. This paper introduces CONCRETE, an open-source library developed in Rust that builds on the state-of-art TFHE cryptosystem. It provides a user-friendly interface making FHE easy to integrate. The library deals with inputs of arbitrary format and comes with an extensive set of operations to play with ciphertexts, including a programmable bootstrapping. CONCRETE is available on GitHub at URL https://github.com/zama-ai/concrete and on https://crates.io.

1 INTRODUCTION

The idea of fully homomorphic encryption (FHE) emerged in 1978 when Rivest, Adleman and Dertouzos started talking about privacy with inputs of arbitrary format and comes with an extensive set without requiring access to the decryption key. This paper introduces CONCRETE, an open-source library developed in Rust that builds on the state-of-art TFHE cryptosystem. It provides a user-friendly interface making FHE easy to integrate. The library deals with inputs of arbitrary format and comes with an extensive set of operations to play with ciphertexts, including a programmable bootstrapping. CONCRETE is available on GitHub at URL https://github.com/zama-ai/concrete and on https://crates.io.

“Concrete Operates on Ciphertexts Rapidly by Extending TFHE”). As for the programming language, we picked Rust, a new language that has become popular thanks to its performance (as good as C or C++ with the advantages of a high-level programming language), its memory safety, and its efficient memory usage and access.

CONCRETE follows TFHE’s implementation: it makes use of arithmetic modulo q with a small modulus natural for a machine such as \( q = 2^{32} \) or \( q = 2^{64} \). This is very convenient because these moduli are natively supported while using unsigned integers with 32 or 64 bits and their respective efficient addition and multiplication operations. Further, CONCRETE unleashes the full potential of TFHE by encrypting and bootstrapping values of arbitrary format, including real numbers. In particular, it is not limited to boolean computation. This is achieved through the use of encoding functions.

The library is designed in layers. The lower-layer level, called Core API, is meant to be accessible by FHE experts and aims to be as efficient as possible. The layer above, named Crypto API, wraps the operator layer in a user-friendly way. It is accessible and easy to use by any programmer (even with a limited understanding of the cryptography behind it). It offers in addition extra capabilities, including automated metadata keeping track of the amount of noise.

2 CRYPTOGRAPHIC CONTENT OF THE LIBRARY

TFHE [2] is based on the learning with errors (LWE) problem [8], a hard problem on lattices, and its variant Ring-LWE [7, 10]. It deals with two types of ciphertexts: LWE ciphertexts and RLWE ciphertexts.

2.1 Encryption & Decryption

LWE ciphertexts. Let \( \mathbb{B} \) denote the set \{0, 1\} and let \( q \) be a power of two. Let also \( \mathbb{Z}_q = \mathbb{Z}/q\mathbb{Z} \). The plaintext space is \( \mathbb{Z}_q \). An LWE ciphertext \( \mathbf{c} \leftarrow \text{LWE}_q(\mu) \) encrypting a plaintext \( \mu \in \mathbb{Z}_q \) under the secret key \( \mathbf{s} = (s_1, \ldots, s_n) \in \mathbb{B}^n \) is a tuple

\[
\mathbf{c} = (a_1, \ldots, a_n, b) \in (\mathbb{Z}_q)^{n+1}
\]

where \( a_1, \ldots, a_n \) are sampled uniformly at random in \( \mathbb{Z}_q \) and

\[
b = \sum_{j=1}^n s_j a_j + \mu + e \pmod q,
\]

with \( e \) a (small) discretized Gaussian noise.

Given a ciphertext \((a_1, \ldots, a_n, b)\), the decryption algorithm uses the secret key \((s_1, \ldots, s_n)\) to obtain \( \mu' := b - \sum_{j=1}^n s_j a_j \equiv \mu + e \pmod q \); see Fig. 1.3. If the message is encoded in the most significant bits (and thus if \( \mu \) has its least significant bits set to zero) then, provided that the noise \( e \) is not too large, rounding \( \mu' \) enables to recover the original \( \mu \).

RLWE ciphertexts. Let \( N \) be a power of two so that \( X^N + 1 \) is the \( 2N \)th cyclotomic polynomial. Let also \( \mathbb{B}_N[X] = \mathbb{B}[X]/(X^N + 1) \).
and $\mathbb{Z}_{q,N}[X] = \mathbb{Z}_q[X]/(X^N + 1)$. The plaintext space for RLWE encryption is $\mathbb{Z}_{q,N}[X]$. An RLWE ciphertext $c \leftarrow \text{RLWE}_q(\mu(X))$, encrypting a plaintext $\mu(X) \in \mathbb{Z}_{q,N}[X]$ under the secret key $\sigma = (\lambda_1(X), \ldots, \lambda_k(X)) \in (\mathbb{Z}[X])^k$ is a tuple
\[
c = (\alpha_1(X), \ldots, \alpha_k(X), \beta(X)) \in (\mathbb{Z}_{q,N}[X])^{k+1}
\]
of $k + 1$ polynomials, where $\alpha_1(X), \ldots, \alpha_k(X)$ are sampled uniformly at random in $\mathbb{Z}_{q,N}[X]$ and $\beta(X) = \sum_{j=1}^{k} \lambda_j(X) \alpha_j(X) + \mu(X) + \epsilon(X) \mod (q, X^N + 1)$, with $\epsilon(X)$ a polynomial with (small) discretized Gaussian coefficients.

Given a ciphertext $(\alpha_1(X), \ldots, \alpha_k(X), \beta(X))$, the decryption proceeds by computing (in $\mathbb{Z}_{q,N}[X]$) the polynomial $\mu^*(X) := \beta(X) - \sum_{j=1}^{k} \lambda_j(X) \alpha_j(X) = \mu(X) + \epsilon(X)$. As for LWE ciphertexts, if the message is encoded in the most significant bits of the coefficients of $\mu^*(X)$, rounding each coefficient of $\mu^*(X)$ yields back the original $\mu(X)$, provided that the noise $\epsilon(X)$ is not too large.

### 2.2 Real Encoding on $[a, b]$  

The plaintext space is defined over $\mathbb{Z}_q$. This section describes how to represent messages of a real domain $\mathcal{D} = [a, b] \subset \mathbb{R}$ with a subset of $\mathbb{Z}_q$. To do so, a number of bits $n_{\text{msg}}$ are reserved to store the message $m \in \mathcal{D}$ as well as a number of padding bits $n_{\text{pad}}$ in the MSBs. There are two different settings for the encoding: (i) the number of precision bits contained in the plaintext is maximized (Fig. 1.4) and (ii) the precision is limited to $n_{\text{msb}}$ bits (Fig. 1.1).

The encoding functions are defined as (i) $\text{Encode}(m \in \mathcal{D}) = \lfloor q (m-a)/(b-a) \rfloor \cdot 2^{n_{\text{msb}}} / \delta$ and as (ii) $\text{Encode}(m \in \mathcal{D}) = \lfloor q (m-a)/(b-a) \rfloor \cdot 2^{n_{\text{msb}}}$. The quantity $\delta$ is a security margin to prevent wrong decryption nearby $0 \in \mathbb{Z}_q$ (i.e., $a$ and $b$ in $\mathcal{D}$), which boils down to actually consider the interval $[a, b + \sigma]$.

The decoding functions of a noisy plaintext $\mu' \in \mathbb{Z}_q$ are defined as (i) rounding $\mu'$ to remove the noise and get $\mu$, and then computing $\text{Decode}(\mu) = a + (\mu - a + \sigma) / \delta$; and (ii) simply computing $\text{Decode}(\mu') = a + \mu' / q \in \mathcal{D}$.

### 2.3 Addition & Scalar Multiplication

LWE ciphertexts can readily be added together (component-wise addition). The result of an addition is an LWE ciphertext in $(\mathbb{Z}_q)^{n+1}$ encrypting the sum (modulo $q$) of the input plaintexts.

This works analogously with RLWE ciphertexts. Note that in both cases the noises also add up as a result of the addition.

**Remark 1.** A way to avoid the modular reduction in the sum of the plaintexts is to make sure that they are small enough. For example, suppose that $q = 2^{32}$ and that plaintexts viewed as 32-bit integers are of the form $\{x \cdot 2^{25}, 0 \leq x < 2^3\}$. This means that plaintexts are made of 2 bits set to zero (i.e., the 2 left-most significant bits—these bits are called padding bits), 5 bits containing the message, and 25 bits set to zero; see Fig. 1.1. Hence, as illustrated in Fig. 1.2, the addition of two such plaintexts yields a plaintext as an element of $\{x \cdot 2^{25}, 0 \leq x < 2^6\}$, that is, with only one bit of padding left.

By extension, LWE (resp. RLWE) ciphertexts can be multiplied by an integer constant. The noise after the scalar multiplication grows proportionally with respect to the integer constant.

### 2.4 External Product

LWE and RLWE ciphertexts can be added; unfortunately, they cannot be multiplied as easily. One may resort to a matrix-based approach [6] to this end. This involves two parameters: a basis $B \in \mathbb{N}$ and a number of levels $t \in \mathbb{N}$. To avoid rounding, it is assumed that $B^t \mid q$.

**RGSW ciphertexts.** An RGSW ciphertext of $\mu(X) \in \mathbb{Z}_N[X]$ under secret key $(\lambda_1(X), \ldots, \lambda_k(X)) \in \mathbb{Z}[X]^k$ is a matrix $\mathcal{C} \in (\mathbb{Z}_{q,N}[X])^{(k+1) \times (k+1)}$ whose row $\#i$ where $i = t + (j-1)t$, for $1 \leq i < t$ and $1 \leq j \leq k+1$, is an RLWE encryption under key $(\lambda_1(X), \ldots, \lambda_k(X))$ of plaintext $\mu_i(X) := -\lambda_j(X) \mu(X) q / B^t$, with $\lambda_{k+1}(X) := -1$. This is written $c \leftarrow \text{RGSW}_q(\mu(X))$.

**External product.** The external product [2, § 3.3] of an RGSW ciphertext $\mathcal{C}_1 \leftarrow \text{RGSW}_q(\mu_1(X))$ and of an RLWE ciphertext $\mathcal{C}_2 \leftarrow \text{RLWE}_q(\mu_2(X))$ is noted $c \mathcal{C}_1 \otimes \mathcal{C}_2$. The resulting ciphertext $c_3$ is an RLWE encryption of $\mu_1(X) \cdot \mu_2(X)$. The external product is defined by $c_1 \otimes c_2 = \mathcal{G}^{-1}(c_2) \cdot \mathcal{G}(c_1)$, where $\mathcal{G}^{-1}(c_2)$ is the gadget decomposition of $c_2$. The transformation $\mathcal{G}^{-1}(\cdot)$ flattens a vector of $(k+1)$ polynomials of $\mathbb{Z}_q[N][X]$ into a row vector of $(k+1)t$ polynomials of $\mathbb{Z}[X]$ with small coefficients in the range $[-B^t/2, B^t/2]$. The use of the gadget decomposition enables to control the noise growth in the external product.

**CMUX.** The main application of the external product in TFHE is the controlled multiplexer, or CMUX in short. Given two RLWE ciphertexts $c_0 \leftarrow \text{RLWE}_q(\mu_0(X))$ and $c_1 \leftarrow \text{RLWE}_q(\mu_1(X))$, the CMUX operator acts as a selector to choose between $c_0$ and $c_1$ according to an RGSW encryption $\mathcal{C}_h \leftarrow \text{RGSW}_q(b)$ of a control bit $b \in \mathbb{B}$. This can be computed through an external product as $\text{CMUX}(c_0, c_1, c_h) = c_0 \oplus (c_1 - c_0) + c_h$. The output is an RLWE encryption of $\mu_h(X)$.

### 2.5 Programmable Bootstrapping

As aforementioned, homomorphic operations may increase the noise in ciphertexts, and when the noise grows too much ciphertexts cannot be decrypted anymore. This is why, from time to time, it is
important to refresh noisy ciphertexts by reducing the amount of noise. Programmable bootstrapping (PBS) is a generalization of the bootstrapping technique allowing resetting the noise at a fixed level while at the same time homomorphically evaluating a function on the input ciphertext.

Programmable bootstrapping involves a series of three algorithms: (i) Switch Modulus, (ii) Blind Rotate, and (iii) Sample Extract. It is often followed by an LWE Key Switching algorithm. These algorithms are described below.

Modulus switching. The modulus switching is a classical technique in FHE for switching the modulus of ciphertexts. In TFHE, a modulus switching is performed prior to the blind rotate procedure. The Switch Modulus algorithm scales by $2N/q$ and rounds (i.e., performs the operation $[2N \cdot (\mod q)/q]$) each component of the input LWE ciphertext (i.e., elements in $\mathbb{Z}_q$).

Blind rotation. The Blind Rotate algorithm homomorphically applies a rotation over the coefficients of the plaintext polynomial stored in an RLWE ciphertext. It is used to blindly put a desired coefficient in the constant term. This algorithm takes on input a (possibly trivial)1 RLWE ciphertext $\mathbf{c}_T \in (\mathbb{Z}_q, N)[X]$ encrypting the test polynomial $T(X) = t_0 + t_1 X + \cdots + t_{N-1} X^{N-1}$, an LWE ciphertext $\mathbf{c} = (a_1, \ldots, a_n, b) \in (\mathbb{Z}_2^n)^{n+1}$ encrypting $\mu$, and an RGSW ciphertexts $\{\mathbf{f}_i\}_{1 \leq i \leq n}$ encrypting each bit of the secret key $s_1, \ldots, s_n \in \mathbb{B}^n$ used to encrypt $\mathbf{c}$. Note that the RGSW ciphertexts and the RLWE ciphertext are encrypted with the same secret key. The noisy plaintext contained in $\mathbf{c}$ is noted $\mu'$.

In Figure 2, the test polynomial is seen as a table where, for $0 \leq i \leq N - 1$, $t[i]$ represents the $i$-th coefficient $t_i$ of $T(X)$, and $t[i + N] = -t_i$. The algorithm starts by initializing an accumulator $\mathbf{ACC} \leftarrow X^{-b} \cdot \mathbf{c}_T$. Next, by using each ciphertext of $\{\mathbf{f}_i\}_{1 \leq i \leq n}$ as control bit into a CMUX, the algorithm successively updates the accumulator as $\mathbf{ACC} \leftarrow \text{CMUX}((\mathbf{f}_j, \mathbf{ACC}, X^{a_j} \cdot \text{ACC})$ for $j = 1, \ldots, n$. The output of an RLWE ciphertext encrypting the plaintext $X^{-b}X_{j_1}^{a_{j_1}}s_{j_1}a_{j_1} \cdots X^{-b}X_{j_n}^{a_{j_n}} \cdot \mathbf{c}_T = X^{-\mu'} \cdot \mathbf{c}_T$ which contains $t[\mu']$ in its constant coefficient.

Sample extraction. It is easy to extract any of the $N$ coefficients inside an RLWE plaintext $\mu(X) = \mu_0 + \mu_1 X + \cdots + \mu_{N-1} X^{N-1} \in \mathbb{Z}_q, N[X]$ as an LWE ciphertext. The corresponding algorithm is called Sample Extract and simply consists in picking some of the coefficients of the input RLWE ciphertext and using them to build the output as an LWE encryption of the desired coefficient $\mu_i$. It is a public operation and adds no noise in the output.

Key switching. After the blind rotation and sample extraction, the resulting LWE ciphertext is encrypted with a secret key that is different from the one used on input. In order to revert to the original key, one needs to perform a key-switching operation (this operation is optional). As for the external product, the corresponding Key Switch algorithm involves two parameters: a basis $B_{i\in N}$ and a number of levels $\ell_{i \in N}$. The input dimension is denoted $n_{\text{in}}$ and the output dimension $n_{\text{out}}$. This procedure is classical in FHE and is possible thanks to the use of a key-switching key; i.e., a list of $n_{\text{in}}$ LWE ciphertexts encrypting each bit of the input secret key

1A trivial RLWE ciphertext for plaintext $\mu(X)$ is a ciphertext of the form $(0, \ldots, 0, \mu(X))$.1

Figure 2: Binary representation of the constant coefficient from the polynomial plaintext encrypted in the accumulator during the Blind Rotate algorithm.
would be easy.

The value of \( q \) is not fixed so that all functions are currently defined for either \( 2^{32} \) or \( 2^{64} \). Note that having functions for \( q = 2^{128} \) would be easy.

The CONCRETE\(^2\) library is built as a stack of layers (Fig. 4) from the closest to the hardware to the most abstracted and easy-to-use (Crypto API). In between, the API called Core API proposes an hardware generic API. At the moment, Core API only provides access to the CPU-based code version, but a GPU version (following the same API) is in preparation. On top of that, the Core API is wrapped in a more user-friendly API called Crypto API where every cryptographic object is represented as a structure. These structures also contain some metadata as the noise distribution, the number of padding bits or the decoding parameters. They are mainly used to ensure the correctness of the comptuation. The noise is monitored by a dedicated module abbreviated as NPE, for Noise Propagation Estimator.

3 CONCRETE IMPLEMENTATION

The CONCRETE\(^2\) library is released under the AGPLv3 license.

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The Fast Fourier Transform (FFT) is used to speed up the polynomial products, as provided by the FFTW\(^4\) implementation. The latter has been slightly modified to be compliant with the

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The idea is to multiply each polynomial coefficient by power of \(e^{i\pi/N}\) for the forward FFT and by power of \(e^{-i\pi/N}\) for the backward FFT. The Fourier representation of the polynomials uses 64-bit floating numbers.

### 3.1 Core API

The Core API is designed as an abstraction of the hardware dedicated code. Then depending on the underlying hardware actually present on the running machine, the API offers multiple choices which do not require any code modification by the end-user. For instance, the Core API offers some SIMD optimizations if supported by the CPU, or even running on a GPU if possible. Note that the latter is currently a mock-up and not open-sourced yet. Despite this convenient abstraction, the API aims to be as low-level as possible in order to yield better performance.

The API is divided into two main modules: (i) math containing non-cryptographic operations such as adding, subtracting or multiplying (unsigned) integers or polynomials, and (ii) crypto containing cryptographic-related operations such as encryption and decryption functions or bootstrapping and key switching functions.

Slices are used to represent messages, plaintexts, ciphertexts and keys. In Rust, a slice is a contiguous sequence of elements but at the end of an array, its size is not known at compile time. A slice contains a pointer to the data and the length of the slice. Messages are stored in slices of f64, and plaintexts, ciphertexts and keys are stored in slices of unsigned integers u32 or u64.

Ciphertexts. Ciphertexts are stored in slices of unsigned 32-bit/64-bit integers. In Core API, functions are able to work on a collection of ciphertexts. This is modeled as a single slice containing several concatenated LWE ciphertexts. For instance, the key switch function can compute a key switch for each of the ciphertexts in the slice.

Secret keys. The LWE or RLWE secret keys are all sampled from a uniform binary distribution. The keys are stored in the same way as ciphertexts: in slices of unsigned 32-bit/64-bit integers such that in the first element of the slice are the 32/64 first bits of the key.

Random source. Uniform random integers are generated with OpenSSL. Discretized Gaussian integers are obtained with a Box-Muller algorithm using OpenSSL uniform random integers.

Benchmarks. Tables 1 and 2 show the time needed to compute a PBS and a key switch for both \(q = 32\) and \(q = 64\). Benchmarks are obtained using Criterion, a Rust micro-benchmarking library. Each measurement is the mean duration of 500 iterations of the operation performed on a single thread.

Benchmarks were made on a personal computer with a 2.6 GHz 6-Core Intel® Core™ i7 processor.

### 3.2 Crypto API

The Crypto API wraps Core API in simple-to-use structures. Typically, metadata are directly included and automatically updated as the Core API homomorphic computation progresses. Code example 1 shows how to pick cryptographic parameters and generate secret keys (Lines 16 and 17), how to define an input encoder (Line 13), how to encode and encrypt a message (Line 23), how to generate a bootstrapping key (Line 20), how to define an output encoder (Line 30), how to homomorphically compute \(c \rightarrow \max(0, \weight \cdot c + \text{bias})\) with a PBS (Lines 36 and 37), and finally how to decrypt (Line 40). Code example 2 shows how to pick cryptographic parameters and how to generate an RLWE secret key (Lines 2 and 3), how to define an input encoder (Line 6), how to encode and encrypt packed messages in RLWE ciphertexts (Lines 7 to 10), how to add two ciphertexts with padding (Line 13), to multiply by constants with padding (Line 14), how to extract an LWE from an RLWE (Line 16), and finally how to decrypt (Line 18).

Structures. The Crypto API introduces the following structures: Encoder, Plaintext, LWESecretKey, RLWESecretKey, LWESK, LWESK, LWEK, LWE, VectorLWE, VectorRLWE, LWEParams, RLWEParams.

Cryptographic parameters. In order to ease the use of the library, some secure cryptographic parameters are offered to the end-user. For instance, in Code example 1, an RLWE secret key is created using &RLWE128_1024_1. Following the notations defined in Section 2, this means that the RLWE key provides 128 bits of security with \(N = 1024\) and \(k = 1\). Similar predefined sets are available for LWE parameters, such as &LWE128_630 providing 128 bits of security with \(n = 630\). The adequate standard noise distribution for each parameter set have been computed via the LWE Estimator [1] in September 2020. Obviously for more advanced users, the cryptographic parameters can easily be set by hand.

---

**Table 1:** PBS in milliseconds from CPU Core API with \(k = 1, B = 2^7\) and \(\ell = 3\).

<table>
<thead>
<tr>
<th>N</th>
<th># bits</th>
<th>(n_{\text{out}} = 630)</th>
<th>(n_{\text{out}} = 800)</th>
<th>(n_{\text{out}} = 1024)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>(n)</td>
<td>32</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>1024</td>
<td>630</td>
<td>15.49</td>
<td>18.08</td>
<td>33.28</td>
</tr>
<tr>
<td>2048</td>
<td>800</td>
<td>19.23</td>
<td>22.98</td>
<td>42.33</td>
</tr>
<tr>
<td>4096</td>
<td>1024</td>
<td>24.54</td>
<td>29.16</td>
<td>54.14</td>
</tr>
</tbody>
</table>

**Table 2:** LWE key switching (in milliseconds) from CPU Core API with \(B_k = 4\) and \(\ell_k = 8\).

<table>
<thead>
<tr>
<th>(n_{\text{in}})</th>
<th># bits</th>
<th>32</th>
<th>64</th>
<th>32</th>
<th>64</th>
<th>32</th>
<th>64</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>630</td>
<td>0.9912</td>
<td>2.292</td>
<td>1.171</td>
<td>2.872</td>
<td>1.518</td>
<td>3.652</td>
</tr>
<tr>
<td>2048</td>
<td>800</td>
<td>2.130</td>
<td>4.661</td>
<td>2.495</td>
<td>5.877</td>
<td>3.200</td>
<td>7.699</td>
</tr>
<tr>
<td>4096</td>
<td>1024</td>
<td>4.413</td>
<td>9.476</td>
<td>5.134</td>
<td>11.89</td>
<td>6.592</td>
<td>15.39</td>
</tr>
</tbody>
</table>

---

1. // generation of a RLWE secret key
2. let rlwe_params = RLWEParams::new(1024, 1, 25);?
3. let rlwe_sk = RLWESecretKey::new(&rlwe_params);
4. // encryption
5. let encoder = Encoder::new(-5, 5, 5, 7);
6. let rlwe_ct_1 = VectorRLWE::encode_encrypt_packed(
7. &rlwe_sk, &[14, -35, 27], &encoder);
8. let rlwe_ct_2 = VectorRLWE::encode_encrypt_packed(
9. &rlwe_sk, &[-31, -22, 0.3], &encoder);
10. // homomorphic operations
11. let mut rlwe_ct_3 = rlwe_ct_1.add_with_padding(&rlwe_ct_2);
12. rlwe_ct_3.mul_constant_with_padding_inplace(&[2.3, 2, -1.5], 2.3, 5);
with the help of the \( k \). Table 4 gives the cost of a PBS and a key switch using the \( f \). The same setting as above is used. The same setting as above is used.

padding bit and is able to add many of them in its output. In the Crypto API, homomorphic operations requiring padding bits are suffixed with _with_padding.

Automatic generation of the look-up table. The Crypto API provides an automatic generation for the look-up table associated to an arbitrary function \( f \) taking as input an \( f64 \) and outputting an \( f64 \), mainly called in the PBS. It takes as inputs the encoding of the inputs, the encoding of the outputs, and the function \( f \).

Benchmarks. Table 3 presents the time needed to compute a multiplication using two PBS’s. The same setting as above is used. Table 4 gives the cost of a PBS and a key switch using the Core API and the Crypto API for the parameter set given in [2].

Code Example 2: A piece of code using CONCRETE’s Crypto API to encrypt packed messages with RLWE and to compute constant multiplication and homomorphic addition before extracting one slot as an LWE ciphertext.

### 3.3 Planned Demo

During the demo, we plan to quickly give an overview of CONCRETE, and then to run live tests for basic operations (both exact and approximate) and for neural network inference.

### 4 FUTURE WORK

The CONCRETE library offers an efficient and user-friendly interface to homomorphically compute over ciphertexts. There is a variety of ways to use encoding such as representing approximation of real numbers. Thanks to the programmable bootstrapping, it is possible to compute non-linear functions in addition to homomorphic additions and multiplications by scalars.

We plan to add other homomorphic operations and features in the next versions of the library. In parallel, we are implementing the GPU version of the Core API level and building an automatic API dealing with padding and noise automatically on its own. Future works also include some studies about enhancing the FFT performance and further support of SIMD operations. Finally, we want to work on the parallelization of the existing code.

### REFERENCES


