

Faster Gaussian Sampling for Trapdoor Lattices with Arbitrary Modulus*

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Abstract

We present improved algorithms for gaussian preimage sampling using the lattice trapdoors of (Micciancio and Peikert, CRYPTO 2012). The MP12 work only offered a highly optimized algorithm for the on-line stage of the computation in the special case when the lattice modulus q is a power of two. For arbitrary modulus q , the MP12 preimage sampling procedure resorted to general lattice algorithms with complexity cubic in the bitsize of the modulus (or quadratic, but with substantial preprocessing and storage overheads.) Our new preimage sampling algorithm (for any modulus q) achieves linear complexity, and has very modest storage requirements. As an additional contribution, we give a new off-line quasi-linear time perturbation sampling algorithm, with performance similar to the (expected) running time of an efficient method proposed by (Ducas and Nguyen, Asiacrypt 2012) for power-of-two cyclotomics, but without the (matrix factorization) preprocessing and (lattice rounding) postprocessing required by that algorithm. All our algorithms are fairly simple, with small hidden constants, and offer a practical alternative to use the MP12 trapdoor lattices in a broad range of cryptographic applications.

1 Introduction

Lattice cryptography provides powerful techniques to build a wide range of advanced cryptographic primitives, like identity based encryption [28, 19, 9, 3, 1, 2], attribute based encryption [14, 13, 15, 30, 12], some types of fully homomorphic encryption and signatures [11, 10, 29, 32, 21], group signatures [33, 17, 37, 38, 47] and much more (e.g., see [49, 44, 8, 50, 54, 5, 39, 31]). Most of the advanced applications of lattice cryptography rely on a notion of strong lattice trapdoor, introduced in [28], which allows to sample points from an n -dimensional lattice L with a gaussian-like distribution. This gaussian sampling operation is often the main bottleneck in the implementation of advanced cryptographic functions that make use of strong lattice trapdoors, and improving the methods to generate and use lattice trapdoors has been the subject of several investigations [4, 28, 6, 48].

The current state of the art in lattice trapdoor generation and sampling is given by [44], which introduces a new notion of lattice trapdoor, specialized to the type of q -ary lattices used in cryptography, i.e., integer lattices $L \subseteq \mathbb{Z}^n$ that are periodic modulo $q \cdot \mathbb{Z}^n$. Building on techniques from [48], this algorithm includes both an on-line and an off-line stage, and [44] focuses on improving the complexity of the on-line stage, which is far more critical in applications. Unfortunately, the most efficient algorithms proposed in [44] for (the on-line stage of) preimage sampling only apply to lattices with modulus $q = 2^k$ equal to a power of 2 (or, more generally, the power $q = p^k$ of a small prime p), which is not compatible with the functional or efficiency requirements of many applications. Moreover, only the on-line stage of [44] takes full advantage of the structure of algebraic lattices [43, 41, 42] typically employed in the efficient instantiation of lattice

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	MP12	MP12	DN12	This work
modulus q	2^k	any	—	any
On-line precomp.	—	$O(\log^3 q)$	—	—
On-line space	$O(1)$	$O(\log^2 q)$	—	$O(1)$
On-line time	$O(\log q)$	$O(\log^2 q)$	—	$O(\log q)$
Off-line precomp.	$O(n^3 \log^3 q)$	$O(n^3 \log^3 q)$	$O(n \log n)$	—
Off-line space	$O(n^2 \log^2 q)$	$O(n^2 \log^2 q)$	$O(n \log n)$	$O(1)$
Off-line time	$O(n^2 \log^2 q)$	$O(n^2 \log^2 q)$	$O(n \log n \log q)$	$O(n \log n \log q)$

Table 1: Running time of the on-line (G-sampling) and off-line (perturbation generation) stage of gaussian preimage sampling for lattices over the n th-cyclotomic ring, n a power of two, and modulus q . On-line running times are scaled by a factor n to take into account that each sample requires n independent calls to the underlying G -sampling operation. Each algorithm includes an optional one-time preprocessing, followed by a computation with the given space and time complexity. The DN12 results listed are the average case complexities and storage.

cryptography, and essential to reduce the running time of lattice operations from quadratic (in the lattice dimension) to quasi-linear. A straightforward implementation of the off-line stage (e.g., using a generic Cholesky decomposition algorithm) completely destroys the algebraic structure, and degrades the running time of the (off-line) algorithm from quasi-linear to quadratic or worse. For lattices over “power-of-two” cyclotomic rings (the most popular class of algebraic lattices used in cryptography), a much faster algorithm for the off-line stage is described in [23, Section 6], which uses a combination of lazy floating-point techniques and numerical analysis methods to improve the (expected) running time of the off-line computation from quadratic to quasilinear, but at the cost of storing the result of a somehow slower precomputation.¹

Our Contribution: We present new, improved algorithms for gaussian preimage sampling using the lattice trapdoors of [44]. Specifically, we present a new algorithm (for the on-line stage) capable of handling any modulus q (including the large prime moduli required by some applications) and still achieve the same level of performance of the specialized algorithm of [44] for power-of-two modulus $q = 2^k$. This improves the running time of [44] for arbitrary modulus from cubic $\log^3 q$ (or quadratic $\log^2 q$, using precomputation and a substantial amount of storage) to just linear in $\log q$ and with minimal storage requirements.

As an additional contribution, we present an alternative to the off-line perturbation generation technique of [23] for power-of-two cyclotomic rings, which takes full advantage of the algebraic structure of ring lattices, but requires no preprocessing or storage. Our approach also generalizes to other cyclotomic rings more easily than [23], and, used in combination with techniques from [42], achieves similar performance for any cyclotomic of smooth order.

These improvements are summarized in Table 1. The improvements are not just asymptotic: our new algorithms are fairly simple, with small hidden constants, and include a careful choice of the parameters that allows to implement most steps using only integer arithmetic on very small numbers. The concrete efficiency of our algorithms, in a range of different cryptographic applications, has been recently confirmed by independent implementation efforts [34, 35, 20, 22]. Taken together, our new algorithms provide a very efficient method to instantiate the lattice trapdoor sampling procedures of [44] in the ring setting, without any restriction on the factorization of the modulus q , and offering a ready-to-use solution to cryptographic applications that make use of lattice preimage sampling.

¹The methods to speed up computations in algebraic lattices are only sketched in [23, Section 6], which refers for details to a full version of the paper that is still to appear. Based on our best understanding of the material presented in the conference proceedings, the precomputation can be as slow as $\tilde{O}(n^{2.5})$, and require the storage of up to $O(n^2)$ bits, depending on the quality of floating point approximation.

Technical details In order to describe our techniques, we need first to provide more details on the lattice trapdoor sampling problem. Given a lattice L and a target point \mathbf{t} , the lattice gaussian sampling problem asks to generate (possibly with the help of some trapdoor information) a random lattice point $\mathbf{v} \in L$ with probability proportional to $\exp(-c\|\mathbf{v} - \mathbf{t}\|^2)$. Building on techniques from [48], this problem is solved in [44] by mapping L to a fixed (key independent) lattice G^n , generating a gaussian sample in G^n , and then mapping the result back to L . (The linear function T mapping G^n to L serves as the trapdoor.) Without further adjustments, this produces a lattice point in L with ellipsoidal gaussian distribution, with covariance which depends on the linear transformation T . In order to produce spherical samples (as required² by applications), [44] employs a perturbation technique from [48] which adds some noise (with complementary covariance) to the target \mathbf{t} , before using it as a center for the G^n -lattice sampling operation. In summary, the sampling algorithm of [48, 44] consists of two stages:

- an off-line (target independent) stage, which generates perturbation vectors with covariance matrix defined by the trapdoor transformation T , and
- an on-line (target dependent) stage which generates gaussian samples from an (easy to sample) lattice G^n .

Not much attention is paid in [44] to the perturbation generation, as it does not depend on the target vector \mathbf{t} , and it is far less time critical in applications.³ As for the on-line stage, one of the properties that make the lattice G^n easy to sample is that it is the orthogonal sum of n copies of a low dimensional lattice G , of dimension $\log q$. So, even using generic algorithms with quadratic running time, G sampling takes a total of $O(n \log^2 q)$ operations. For moduli $q = n^{O(1)}$ polynomial in the lattice dimension n , this results in quasilinear running time $O(n \log^2 n)$. However, since the G -sampling operation directly affects the on-line running time of the signing algorithm, even a polylogarithmic term $\log^2 q$ can be highly undesirable. To this end, [44] gives a particularly efficient (and easy to implement) algorithm for G -lattice sampling when the lattice modulus $q = 2^k$ is a power of 2 (or more generally, a power $q = p^k$ of a small prime p .) The running time of this specialized G -sampling algorithm is $\log q$, just linear in the lattice dimension, and has minimal (constant) storage requirements. Thanks to its simplicity and efficiency, this algorithm has easily found its way in concrete implementations of lattice based cryptographic primitives (e.g., see [7]), largely solving the problem of efficient lattice sampling for $q = 2^k$. However, setting q to a power of 2 (or more generally, the power of a small prime), may be incompatible with applications and other techniques used in lattice cryptography, like ciphertext packing techniques in fully homomorphic encryption [27] and fast implementation via the number theoretic transform [40, 42]. For arbitrary modulus q , [44] falls back to generic algorithms (for arbitrary lattices) with quadratic complexity. This may still be acceptable when the modulus q is relatively small. But it is nevertheless undesirable, as even polylogarithmic factors have a significant impact on the practical performance of cryptographic functions (easily increasing running times by an order of magnitude), and can make applications completely unusable when the modulus $q = \exp(n)$ is exponentially large. A concrete example that well illustrates the limitations of [44] is the recent conjunction obfuscator of [16], which requires the modulus q to be prime with bitsize $\log(q) = O(n)$ linear in the security parameter. In this setting, the specialized algorithm of [44] (for $q = 2^k$) is not applicable, and using a generic algorithm slows down the on-line stage by a factor $O(n)$.

Unfortunately, the specialized algorithm from [44] makes critical use of the structure of the G -basis when $q = 2^k$, and is not easily adapted to other moduli. (See Section 3 for details.) In order to solve this problem we resort to the same technique used in [48, 44] to generate samples from arbitrary lattices: we map G to an even simpler lattice D using an easy to compute linear transformation T' , perform the gaussian sampling in D , and map the result back to G . As usual, the error shape is corrected by including a perturbation term with appropriate covariance matrix. The main technical problem to be solved is to find a suitable linear transformation T' such that D can be efficiently sampled and perturbation terms can be easily

²More generally, applications require samples to be generated according to a distribution that does not depend on the trapdoor/secret key.

³E.g., in lattice based digital signature schemes [28, 44], the off-line computation depends only on the secret key, and can be performed in advance without knowing the message to be signed.

generated. In Section 3 we demonstrate a choice of transformation T' with all these desirable properties. In particular, using a carefully chosen transformation T' , we obtain lattices D and perturbation matrices that are triangular, sparse, and whose entries admit a simple (and efficiently computable) closed formula expression. So, there is not even a need to store these sparse matrices explicitly, as their entries can be easily computed on the fly. This results in a G-sampling algorithm with linear running time, and minimal (constant) space requirements, beyond the space necessary to store the input, output and randomness of the algorithm.

Next, in Section 4, we turn to the problem of efficiently generating the perturbations of the off-line stage. Notice that generating these perturbations is a much harder problem than the one faced when mapping G to D (via T'). The difference is that while G, D, T' are fixed (sparse, carefully designed) matrices, the transformation T is a randomly chosen matrix that is used as secret key. In this setting, there is no hope to reduce the computation time to linear in the lattice dimension, because even reading/writing the matrix T can in general take quadratic space. Still, when using algebraic lattices, matrix T admits a compact (linear size) representation, and one can reasonably hope for faster perturbation generation algorithms, but [44] gives no indication of how to achieve this. The off-line algorithm of [44] includes both a preprocessing (matrix factorization) and postprocessing (lattice rounding) stage. Implementing the preprocessing using standard Cholesky decomposition techniques (as mentioned in [44] for arbitrary lattices) immediately destroys all the algebraic structure in the trapdoor, and results in very poor performance. An asymptotically superior preprocessing method, which preserves the algebraic structure, is proposed in [23] for the important case of power-of-two cyclotomic rings. More specifically, [23, Section 6] observes that when working in such rings, one can replace the Cholesky decomposition with a factorization over ring elements that admits both a compact representation and an efficient algorithm to compute it. The algorithms of [44, 23] are otherwise identical, consisting of a preprocessing (matrix factorization) stage, noise generation over the reals, and postprocessing (lattice rounding) step to map the noise to an appropriate integer lattice. We present an alternative algorithm that uses the subring structure of power-of-two cyclotomic rings to completely bypass the need to precompute any matrix factorization, and directly generates perturbation vectors in the target lattice. In summary, our recursive algorithm efficiently generates the perturbation vectors (in quasilinear time, and with very modest storage requirements), requiring neither the matrix factorization preprocessing nor the lattice rounding postprocessing of [44, 23]. Lastly, while the techniques in [23] seem specific to the power-of-two cyclotomic ring setting, our algorithm generalizes to perturbation sampling in arbitrary cyclotomic rings, and can be implemented efficiently whenever the order of the cyclotomic ring is smooth. Our techniques are related to the fast fourier orthogonalization algorithm of [24], but solve a different problem altogether.

2 Preliminaries

We denote the complex numbers as \mathbb{C} , the real numbers as \mathbb{R} , the rational numbers as \mathbb{Q} , and the integers as \mathbb{Z} . A number is denoted by a lower case letter, $n \in \mathbb{Z}$ for example. We denote the conjugate of a complex number y as y^* . When q is a positive integer, $\log q$ is short for its rounded up logarithm in base two, $\lceil \log_2 q \rceil$. The index set of the first n natural numbers is $[n] = \{1, \dots, n\}$. Vectors are denoted by bold lower case letters, \mathbf{v} , and are in column form (\mathbf{v}^T is a row vector) unless stated otherwise. The inner product of two vectors is $\langle \mathbf{x}, \mathbf{y} \rangle = \mathbf{x}^T \mathbf{y}$. We denote matrices with bold upper case letters \mathbf{B} or with upper case Greek letters (for positive-definite matrices). In addition, we denote the transpose of a matrix as \mathbf{B}^T , and its Hermitian transpose as \mathbf{B}^\dagger . The entry of \mathbf{B} in row i and column j is denoted $B_{i,j}$. Unless otherwise stated, the norm of a vector is the ℓ_2 norm. The norm of a matrix $\|\mathbf{B}\| = \max_i \|\mathbf{b}_i\|$ is the maximum norm of its column vectors. Given two probability distributions over a countable domain D , the statistical distance between them is $\Delta(X, Y) = \frac{1}{2} \sum_{\omega \in D} |X(\omega) - Y(\omega)|$. For a random variable X , we denote its expectation as $\mathbb{E}[X]$. Expectation is extended coordinate-wise to random vectors. We denote a random variable x sampled from a distribution \mathcal{A} as $x \leftarrow \mathcal{A}$. A random variable distributed as \mathcal{A} is denoted $x \sim \mathcal{A}$.

2.1 Linear Algebra

The *Gram-Schmidt orthogonalization* of an ordered set of linearly independent vectors $\mathbf{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_k\}$ is $\tilde{\mathbf{B}} = \{\tilde{\mathbf{b}}_1, \dots, \tilde{\mathbf{b}}_k\}$ where each $\tilde{\mathbf{b}}_i$ is the component of \mathbf{b}_i orthogonal to $\text{span}(\mathbf{b}_1, \dots, \mathbf{b}_{i-1})$. An *anti-cyclic* matrix is an $n \times n$ matrix of the form

$$\begin{bmatrix} a_0 & -a_{n-1} & \dots & -a_1 \\ a_1 & a_0 & \dots & -a_2 \\ \vdots & \vdots & \ddots & \vdots \\ a_{n-1} & a_{n-2} & \dots & a_0 \end{bmatrix}.$$

For any two (symmetric) matrices $\Sigma, \Gamma \in \mathbb{R}^{n \times n}$, we write $\Sigma \succeq \Gamma$ if $\mathbf{x}^T(\Sigma - \Gamma)\mathbf{x} \geq 0$ for all (nonzero) vectors $\mathbf{x} \in \mathbb{R}^n$, and $\Sigma \succ \Gamma$ if $\mathbf{x}^T(\Sigma - \Gamma)\mathbf{x} > 0$. It is easy to check that \succeq is a partial order relation. Relations \preceq and \prec are defined symmetrically. When one of the two matrices $\Gamma = s\mathbf{I}$ is scalar, we simply write $\Sigma \succeq s$ or $\Sigma \preceq s$. A symmetric matrix $\Sigma \in \mathbb{R}^{n \times n}$ is called *positive definite* if $\Sigma \succ 0$, and *positive semidefinite* if $\Sigma \succeq 0$. Equivalently, Σ is positive semidefinite if and only if it can be written as $\Sigma = \mathbf{B}\mathbf{B}^T$ for some (square) matrix \mathbf{B} , called a *square root* of Σ and denoted $\mathbf{B} = \sqrt{\Sigma}$. (Notice that any $\Sigma \succ 0$ has infinitely many square roots $\mathbf{B} = \sqrt{\Sigma}$.) Σ is positive definite if and only if its square root \mathbf{B} is a square nonsingular matrix. When \mathbf{B} is upper (resp. lower) triangular, the factorization $\Sigma = \mathbf{B}\mathbf{B}^T$ is called the upper (resp. lower) triangular *Cholesky decomposition* of Σ . The Cholesky decomposition of any positive definite $\Sigma \in \mathbb{R}^{n \times n}$ can be computed with $O(n^3)$ floating point arithmetic operations. For any scalar s , $\Sigma \succ s$ if all eigenvalues of Σ are strictly greater than s . In particular, positive definite matrices are nonsingular.

For any $n \times n$ matrix \mathbf{S} and index sets $I, J \subseteq \{1, \dots, n\}$, we write $\mathbf{S}[I, J]$ for the $|I| \times |J|$ matrix obtained by selecting the elements at positions $(i, j) \in I \times J$ from \mathbf{S} . When $I = J$, we write $\mathbf{S}[I]$ as a shorthand for $\mathbf{S}[I, I]$. Notice that for any nonsingular matrix $\mathbf{S} \in \mathbb{R}^{n \times n}$, and index set $I \subseteq \{1, \dots, n\}$, the submatrix $\mathbf{S}[I]$ is also nonsingular. For any nonsingular matrix $\mathbf{S} \in \mathbb{R}^{n \times n}$ and index partition $I \cup \bar{I} = \{1, \dots, n\}$, $I \cap \bar{I} = \emptyset$, the $I \times I$ matrix

$$\mathbf{S}/I = \mathbf{S}[I] - \mathbf{S}[I, \bar{I}] \cdot \mathbf{S}[\bar{I}]^{-1} \cdot \mathbf{S}[\bar{I}, I]$$

is called the *Schur complement* of $\mathbf{S}[\bar{I}]$, often denoted by $\mathbf{S}/\mathbf{S}[\bar{I}] = \mathbf{S}/I$. In particular, if $\mathbf{S} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{D} \end{bmatrix}$ then the Schur complement of \mathbf{A} is the matrix $\mathbf{S}/\mathbf{A} = \mathbf{D} - \mathbf{B}^T\mathbf{A}^{-1}\mathbf{B}$. For any index set I , a symmetric matrix \mathbf{S} is positive definite if and only if both $\mathbf{S}[I]$ and its Schur's complement $\mathbf{S}/\mathbf{S}[I]$ are positive definite.

The next two theorems regarding the spectra of principal submatrices and Schur complements of positive definite matrices are used in Section 4. In both theorems, λ_i is the i th (in non-increasing order, with multiplicity) eigenvalue of a symmetric matrix.

Theorem 1 (Cauchy) For any symmetric matrix $\mathbf{S} \in \mathbb{R}^{n \times n}$, $I \subseteq \{1, \dots, n\}$ and $1 \leq i \leq |I|$

$$\lambda_i(\mathbf{S}) \geq \lambda_i(\mathbf{S}[I]) \geq \lambda_{i+n-|I|}(\mathbf{S}).$$

Theorem 2 ([55, Corollary 2.3]) For any positive definite $\Sigma \in \mathbb{R}^{n \times n}$, $I \subseteq \{1, \dots, n\}$ and $1 \leq i \leq |I|$

$$\lambda_i(\Sigma) \geq \lambda_i(\Sigma/I) \geq \lambda_{i+n-|I|}(\Sigma).$$

In other words, the eigenvalues of principal submatrices and Schur complements of a positive definite matrix are bounded from below and above by the smallest and largest eigenvalues of the original matrix, respectively.

2.2 Gaussians and Lattices

A *lattice* $\Lambda \subset \mathbb{R}^n$ is a discrete subgroup of \mathbb{R}^n . Specifically, a lattice of *rank* k is the integer span $\mathcal{L}(\mathbf{B}) = \{z_1\mathbf{b}_1 + \dots + z_k\mathbf{b}_k \mid z_i \in \mathbb{Z}\}$ of a basis $\mathbf{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_k\} \subset \mathbb{R}^n$ ($k \leq n$). There are infinitely many bases for a given lattice since right multiplying a basis by a unimodular transformation gives another basis. The *dual*

lattice of Λ , denoted by Λ^* , is the lattice $\{\mathbf{x} \in \text{span}(\Lambda) \mid \langle \mathbf{x}, \Lambda \rangle \subseteq \mathbb{Z}\}$. It is easy to see that \mathbf{B}^{-T} is a basis for $\mathcal{L}(\mathbf{B})^*$ for a full rank lattice ($n = k$).

The n -dimensional *gaussian* function $\rho : \mathbb{R}^n \rightarrow (0, 1]$ is defined as $\rho(\mathbf{x}) := \exp(-\pi\|\mathbf{x}\|^2)$. Applying an invertible linear transformation \mathbf{B} to the gaussian function yields

$$\rho_{\mathbf{B}}(\mathbf{x}) = \rho(\mathbf{B}^{-1}\mathbf{x}) = \exp(-\pi \cdot \mathbf{x}^T \Sigma^{-1} \mathbf{x})$$

with $\Sigma = \mathbf{B}\mathbf{B}^T \succeq 0$. For any $\mathbf{c} \in \text{span}(\mathbf{B}) = \text{span}(\Sigma)$, we also define the shifted gaussian function (centered at \mathbf{c}) as $\rho_{\sqrt{\Sigma}, \mathbf{c}}(\mathbf{x}) = \rho_{\sqrt{\Sigma}}(\mathbf{x} - \mathbf{c})$. Normalizing the function $\rho_{\mathbf{B}, \mathbf{c}}(\mathbf{x})$ by the measure of $\rho_{\mathbf{B}, \mathbf{c}}$ over the span of \mathbf{B} gives the *continuous gaussian distribution* with covariance $\Sigma/(2\pi)$, denoted by $D_{\sqrt{\Sigma}, \mathbf{c}}$. Let $S \subset \mathbb{R}^n$ be any discrete set in \mathbb{R}^n , then $\rho_{\sqrt{\Sigma}}(S) = \sum_{\mathbf{s} \in S} \rho_{\sqrt{\Sigma}}(\mathbf{s})$. The *discrete gaussian* distribution over a lattice Λ , denoted by $D_{\Lambda, \sqrt{\Sigma}, \mathbf{c}}$, is defined by restricting the support of the distribution to Λ . Specifically, a sample $\mathbf{y} \leftarrow D_{\Lambda, \sqrt{\Sigma}, \mathbf{c}}$ has probability mass function $\rho_{\sqrt{\Sigma}, \mathbf{c}}(\mathbf{x})/\rho_{\sqrt{\Sigma}, \mathbf{c}}(\Lambda)$ for all $\mathbf{x} \in \Lambda$. Discrete gaussians on lattice cosets $\Lambda + \mathbf{c}$, for $\mathbf{c} \in \text{span}(\Lambda)$, are defined similarly setting $\Pr\{\mathbf{y} \leftarrow D_{\Lambda + \mathbf{c}, \sqrt{\Sigma}, \mathbf{p}}\} = \rho_{\sqrt{\Sigma}, \mathbf{p}}(\mathbf{y})/\rho_{\sqrt{\Sigma}, \mathbf{p}}(\Lambda + \mathbf{c})$ for all $\mathbf{y} \in \Lambda + \mathbf{c}$. For brevity we let $D_{\Lambda + \mathbf{c}, \sqrt{\Sigma}, \mathbf{p}}(\mathbf{y}) := \Pr\{\mathbf{y} \leftarrow D_{\Lambda + \mathbf{c}, \sqrt{\Sigma}, \mathbf{p}}\}$.

For a lattice Λ and any (typically small) positive $\epsilon > 0$, the *smoothing parameter* $\eta_\epsilon(\Lambda)$ [45] is the smallest $s > 0$ such that $\rho(s \cdot \Lambda^*) \leq 1 + \epsilon$. More generally, for any positive definite matrix Σ and lattice $\Lambda \subset \text{span}(\Sigma)$, we write $\sqrt{\Sigma} \geq \eta_\epsilon(\Lambda)$ if $\rho(\sqrt{\Sigma}^T \cdot \Lambda^*) \leq 1 + \epsilon$. The reader is referred to [45, 28, 48] for additional information on the smoothing parameter. Here we recall two bounds and a discrete gaussian convolution theorem to be used later.

Lemma 2.1 ([28, Lemma 3.1]) *Let $\Lambda \subset \mathbb{R}^n$ be a lattice with basis \mathbf{B} , and let $\epsilon > 0$. Then,*

$$\eta_\epsilon(\Lambda) \leq \|\tilde{\mathbf{B}}\| \sqrt{\log(2n(1 + 1/\epsilon))}/\pi.$$

Lemma 2.2 ([48, Lemma 2.5]) *Let Λ be any full rank n -dimensional lattice. For any $\epsilon \in (0, 1)$, $\Sigma \succ 0$ such that $\sqrt{\Sigma} \geq \eta_\epsilon(\Lambda)$, and any $\mathbf{c} \in \mathbb{R}^n$,*

$$\rho_{\sqrt{\Sigma}}(\Lambda + \mathbf{c}) \in \left[\frac{1 - \epsilon}{1 + \epsilon}, 1 \right] \cdot \rho_{\sqrt{\Sigma}}(\Lambda).$$

Theorem 3 ([48, Theorem 3.1]) *For any vectors $\mathbf{c}_1, \mathbf{c}_2 \in \mathbb{R}^n$, lattices $\Lambda_1, \Lambda_2 \subset \mathbb{R}^n$, and positive definite matrices $\Sigma_1, \Sigma_2 \succ 0$, $\Sigma = \Sigma_1 + \Sigma_2 \succ 0$, $\Sigma_3^{-1} = \Sigma_1^{-1} + \Sigma_2^{-1} \succ 0$, if $\sqrt{\Sigma_1} \geq \eta_\epsilon(\Lambda_1)$ and $\sqrt{\Sigma_2} \geq \eta_\epsilon(\Lambda_2)$ for some $0 < \epsilon \leq 1/2$, then the distribution*

$$X = \{\mathbf{x} \mid \mathbf{p} \leftarrow D_{\Lambda_2 + \mathbf{c}_2, \sqrt{\Sigma_2}}, \mathbf{x} \leftarrow D_{\Lambda_1 + \mathbf{c}_1, \sqrt{\Sigma_1}, \mathbf{p}}\}$$

is within statistical distance $\Delta(X, Y) \leq 8\epsilon$ from the discrete gaussian $Y = D_{\Lambda_1 + \mathbf{c}_1, \sqrt{\Sigma}}$. Moreover, the probability of each sample $x \sim X$ is within an interval of $[1 - 16\epsilon, 1 + 16\epsilon]$ of the probability mass function of Y at x , in other words $\Pr_X\{\mathbf{a}\} \in [1 - 16\epsilon, 1 + 16\epsilon] \cdot \Pr_Y\{\mathbf{a}\}$ for all $\mathbf{a} \in \Lambda_1 + \mathbf{c}_1$.

2.3 Cyclotomic Fields

Let n be a positive integer. The n -th *cyclotomic field* over \mathbb{Q} is the number field $\mathcal{K}_n = \mathbb{Q}[x]/(\Phi_n(x)) \cong \mathbb{Q}(\zeta)$ where ζ is an n -th *primitive root of unity* and $\Phi_n(x)$ is the minimal polynomial of ζ over \mathbb{Q} . The n th *cyclotomic ring* is $\mathcal{O}_n = \mathbb{Z}[x]/(\Phi_n(x))$. Let $\varphi(n)$ be Euler's totient function. \mathcal{K}_n is a $\varphi(n)$ -dimensional \mathbb{Q} -vector space, and we can view \mathcal{K}_n as a subset of \mathbb{C} by viewing ζ as a complex primitive n -th root of unity.

Multiplication by a fixed element $f, g \mapsto f \cdot g$, is a linear transformation on \mathcal{K}_n as a \mathbb{Q} -vector space. We will often view field elements as $\varphi(n)$ -dimensional rational vectors via the *coefficient embedding*. This is defined by $f(x) = \sum_{i=0}^{\varphi(n)-1} f_i x^i \mapsto (f_0, \dots, f_{\varphi(n)-1})^T$ mapping a field element to its vector of coefficients under the *power basis* $\{1, x, \dots, x^{\varphi(n)-1}\}$ (or equivalently $\{1, \zeta, \dots, \zeta^{\varphi(n)-1}\}$). We can represent a field element as the matrix in $\mathbb{Q}^{\varphi(n) \times \varphi(n)}$ that represents the linear transformation by its multiplication in the

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SAMPLEG( $q = b^k, s, u$ )
  for  $i = 0, \dots, k - 1$  :
     $x_i \leftarrow \mathcal{D}_{b\mathbb{Z}+u, s}$ 
     $u := (u - x_i)/b \in \mathbb{Z}$ .
  return  $(x_0, \dots, x_{k-1})$ .

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Figure 1: A sampling algorithm for G -lattices when the modulus q is a perfect power of the base b . The algorithm is implicitly parametrized by a base b and dimension k .

coefficient embedding. This matrix is called a field element's coefficient *multiplication* matrix. When n is a power of two, an element's coefficient multiplication matrix is anti-cyclic.

An *isomorphism* from the field F to the field K is a bijection $\theta : F \rightarrow K$ such that $\theta(fg) = \theta(f)\theta(g)$, and $\theta(f + g) = \theta(f) + \theta(g)$ for all $f, g \in F$. An *automorphism* is an isomorphism from a field to itself. For example, if we view the cyclotomic field \mathcal{K}_n as a subset of the complex numbers, then the *conjugation* map $f(\zeta) \mapsto f(\zeta)^* = f(\zeta^*)$ is an automorphism and can be computed in linear time $O(n)$. In power-of-two cyclotomic fields, the conjugation of a field element corresponds to the matrix transpose of an element's anti-cyclic multiplication matrix.

Another embedding is the *canonical* embedding which maps an element $f \in \mathcal{K}_n$ to the vector of evaluations of f , as a polynomial, at each root of $\Phi_n(x)$. When n is a power of two, the linear transformation between the coefficient embedding and the canonical embedding is a scaled isometry.

3 Sampling G-lattices

For any positive integers $b \geq 2, k \geq 1$ and non-negative integer $u < b^k$, we write $[u]_b^k$ for the base- b expansion of u , i.e., the unique vector (u_0, \dots, u_{k-1}) with entries $0 \leq u_i < b$ such that $u = \sum_i u_i b^i$. Typically, $b = 2$ and $[u]_2^k$ is just the k -digits binary representation of u , but larger values of b may be used to obtain interesting efficiency trade-offs. Throughout this section, we consider the values of b and k as fixed, and all definitions and algorithms are implicitly parametrized by them.

In this section we study the so-called G-lattice sampling problem, i.e., the problem of sampling the discrete Gaussian distribution on a lattice coset

$$\Lambda_u^\perp(\mathbf{g}^T) = \{\mathbf{z} \in \mathbb{Z}^k : \mathbf{g}^T \mathbf{z} = u \pmod{q}\}$$

where $q \leq b^k, u \in \mathbb{Z}_q$ and $\mathbf{g} = (1, b, \dots, b^{k-1})$. A very efficient algorithm to solve this problem is given in [44] for the special case when $q = b^k$ is a power of the base b . The algorithm, shown in Figure 1, is very simple. This algorithm reduces the problem of sampling the k -dimensional lattice coset $\Lambda_u^\perp(\mathbf{g}^T)$ for $u \in \mathbb{Z}_q$ to the much simpler problem of sampling the *one-dimensional* lattice cosets $u + b\mathbb{Z}$ for $u \in \mathbb{Z}_b$. The simplicity of the algorithm is due to the fact that, when $q = b^k$ is an exact power of b , the lattice $\Lambda^\perp(\mathbf{g}^T)$ has a very special basis

$$\mathbf{B}_{b^k} = \begin{bmatrix} b & & & & & \\ -1 & b & & & & \\ & -1 & \ddots & & & \\ & & \ddots & b & & \\ & & & -1 & b & \end{bmatrix}$$

which is sparse, triangular, and with small integer entries. (In particular, its Gram-Schmidt orthogonalization $\tilde{\mathbf{B}}_{b^k} = b\mathbf{I}$ is a scalar matrix.) As a result, the general lattice sampling algorithm of [36, 28] (which typically requires $O(k^3)$ -time preprocessing, and $O(k^2)$ storage and online running time) can be specialized to the much simpler algorithm in Figure 1 that runs in linear time $O(k)$, with minimal memory requirements and no preprocessing at all.

We give a specialized algorithm to solve the same sampling problem when $q < b^k$ is an arbitrary modulus. This is needed in many cryptographic applications where the modulus q is typically a prime. As already observed in [44] the lattice $\Lambda^\perp(\mathbf{g}^T)$ still has a fairly simple and sparse basis matrix

$$\mathbf{B}_q = \begin{bmatrix} b & & & & q_0 \\ -1 & b & & & q_1 \\ & -1 & \ddots & & \vdots \\ & & \ddots & b & q_{k-2} \\ & & & -1 & q_{k-1} \end{bmatrix}$$

where $(q_0, \dots, q_{k-1}) = [q]_b^k = \mathbf{q}$ is the base- b representation of the modulus q . This basis still has good geometric properties, as all vectors in its (left-to-right) Gram-Schmidt orthogonalization have length at most $O(b)$. So, it can be used with the algorithm of [36, 28] to generate good-quality gaussian samples on the lattice cosets with small standard deviation. However, since the basis is no longer triangular, its Gram-Schmidt orthogonalization is not sparse anymore, and the algorithm of [36, 28] can no longer be optimized to run in linear time as in Figure 1. In applications where $q = n^{O(1)}$ is polynomial in the security parameter n , the matrix dimension $k = O(\log n)$ is relatively small, and the general sampling algorithm (with $O(k^2)$ storage and running time) can still be used with an acceptable (albeit significant) performance degradation. However, for larger q (e.g., fully homomorphic encryption schemes with exponential $q = 2^{O(n)}$) this becomes prohibitive in practice. Moreover, even for small q , it would be nice to have a sampling algorithm with $O(k)$ running time, linear in the matrix dimension, as for the exact power case. Here we give such an algorithm, based on the convolution methods of [48], but specialized with a number of concrete technical choices that result in a simple and very fast implementation, comparable to the specialized algorithm of [44] for the exact power case.

Overview The idea is the following. Instead of sampling $\Lambda_u^\perp(\mathbf{g}^T)$ directly, we express the lattice basis $\mathbf{B}_q = \mathbf{T}\mathbf{D}$ as the image (under a linear transformation \mathbf{T}) of some other matrix \mathbf{D} with very simple (sparse, triangular) structure. Next, we sample the discrete gaussian distribution (say, with variance σ^2) on an appropriate coset of $\mathcal{L}(\mathbf{D})$. Finally, we map the result back to the original lattice applying the linear transformation \mathbf{T} to it. Notice that, even if $\mathcal{L}(\mathbf{D})$ is sampled according to a spherical gaussian distribution, the resulting distribution is no longer spherical. Rather, it follows an ellipsoidal gaussian distribution with (scaled) covariance $\sigma^2\mathbf{T}\mathbf{T}^T$. This problem is solved using the convolution method of [48], i.e., initially adding a perturbation with complementary covariance $s^2\mathbf{I} - \sigma^2\mathbf{T}\mathbf{T}^T$ to the target, so that the final output has covariance $\sigma^2\mathbf{T}\mathbf{T}^T + (s^2\mathbf{I} - \sigma^2\mathbf{T}\mathbf{T}^T) = s^2\mathbf{I}$. In summary, at a very high level, the algorithm performs (at least implicitly) the following steps:

1. Compute the covariance matrix $\Sigma_1 = \mathbf{T}\mathbf{T}^T$ and an upper bound r on the spectral norm of $\mathbf{T}\mathbf{T}^T$
2. Compute the complementary covariance matrix $\Sigma_2 = r^2\mathbf{I} - \Sigma_1$
3. Sample $\mathbf{p} \leftarrow D_{\Lambda_1, \sigma\sqrt{\Sigma_2}}$, from some convenient lattice Λ_1 using the Cholesky decomposition of Σ_2
4. Compute the preimage $\mathbf{c} = \mathbf{T}^{-1}(\mathbf{u} - \mathbf{p})$
5. Sample $\mathbf{z} \leftarrow D_{\mathcal{L}(\mathbf{D}), -\mathbf{c}, \sigma}$
6. Output $\mathbf{u} + \mathbf{T}\mathbf{z}$

The technical challenge is to find appropriate matrices \mathbf{T} and \mathbf{D} that lead to a very efficient implementation of all the steps. In particular, we would like \mathbf{T} to be a very simple matrix (say, sparse, triangular, and with small integer entries) so that \mathbf{T} has small spectral norm, and both linear transformations \mathbf{T} and \mathbf{T}^{-1} can be computed efficiently. The matrix \mathbf{D} (which is uniquely determined by \mathbf{B} and \mathbf{T}) should also be sparse and triangular, so that the discrete gaussian distribution on the cosets of $\mathcal{L}(\mathbf{D})$ can be efficiently sampled.

Finally (and this is the trickiest part in obtaining an efficient instantiation) the complementary covariance matrix $\Sigma_2 = r^2\mathbf{I} - \Sigma_1$ should also have a simple Cholesky decomposition $\Sigma_2 = \mathbf{L}\mathbf{L}^T$ where \mathbf{L} is triangular, sparse and with small entries, so that perturbations can be generated efficiently. Ideally, all matrices should also have a simple, regular structure, so that they do not need to be stored explicitly, and can be computed on the fly with minimal overhead.

In the next subsection we provide an instantiation that satisfies all of these properties. Next, in Subsection 3.2 we describe the specialized sampling algorithm resulting from the instantiation, and analyze its correctness and efficiency properties.

3.1 Instantiation

In this subsection, we describe a specific choice of linear transformations and matrix decompositions that satisfies all our desiderata, and results in a very efficient instantiation of the convolution sampling algorithm on G -lattices.

A tempting idea may be to map the lattice basis \mathbf{B}_q to the basis \mathbf{B}_{b^k} , and then use the efficient sampling algorithm from Figure 1. However, this does not quite work because it results in a pretty bad transformation \mathbf{T} which has both poor geometrical properties and a dense matrix representation. It turns out that a very good choice for a linear transformation \mathbf{T} is given precisely by the matrix $\mathbf{T} = \mathbf{B}_{b^k}$ describing the basis when q is a power of b . We remark that \mathbf{T} is used as a linear transformation, rather than a lattice basis. So, the fact that it equals \mathbf{B}_{b^k} does not seem to carry any special geometric meaning, it just works! In particular, what we do here should not be confused with mapping \mathbf{B}_q to \mathbf{B}_{b^k} . The resulting factorization is

$$\mathbf{B}_q = \begin{bmatrix} b & & & & q_0 \\ -1 & b & & & q_1 \\ & & \ddots & & \vdots \\ & & & b & q_{k-2} \\ & & & -1 & q_{k-1} \end{bmatrix} = \begin{bmatrix} b & & & & \\ -1 & b & & & \\ & & -1 & \ddots & \\ & & & \ddots & b \\ & & & & -1 & b \end{bmatrix} \begin{bmatrix} 1 & & & & d_0 \\ & 1 & & & d_1 \\ & & \ddots & & \vdots \\ & & & 1 & d_{k-2} \\ & & & & d_{k-1} \end{bmatrix} = \mathbf{B}_{b^k} \mathbf{D}$$

where the entries of the last column of \mathbf{D} are defined by the recurrence $d_i = \frac{d_{i-1} + q_i}{b}$ with initial condition $d_{-1} = 0$. Notice that all the d_i are in the range $[0, 1)$, and $b^{i+1} \cdot d_i$ is always an integer. In some sense, sampling from $\mathcal{L}(\mathbf{D})$ is even easier than sampling from $\mathcal{L}(\mathbf{B}_{b^k})$ because the first $k - 1$ columns of \mathbf{D} are orthogonal and the corresponding coordinates can be sampled independently in parallel. (This should be contrasted with the sequential algorithm in Figure 1.)

We now look at the geometry and algorithmic complexity of generating perturbations. The covariance matrix of $\mathbf{T} = \mathbf{B}_{b^k}$ is given by

$$\Sigma_1 = \mathbf{B}_{b^k} \mathbf{B}_{b^k}^T = \begin{bmatrix} b^2 & -b & & & \\ -b & (b^2 + 1) & -b & & \\ & \ddots & \ddots & \ddots & \\ & & -b & (b^2 + 1) & -b \\ & & & -b & (b^2 + 1) \end{bmatrix}.$$

The next step is to find an upper bound r^2 on the spectral norm of Σ_2 , and compute the Cholesky decomposition $\mathbf{L}\mathbf{L}^T$ of the complementary covariance matrix $\Sigma_2 = r^2\mathbf{I} - \Sigma_1$. By the Gershgorin circle theorem, all eigenvalues of Σ_1 are in the range $(b \pm 1)^2$. So, we may set $r = b + 1$. Numerical computations also suggest that this choice of r is optimal, in the sense that the spectral norm of Σ_1 approaches $b + 1$ as k tends to infinity. The Cholesky decomposition is customarily defined by taking \mathbf{L} to be a *lower* triangular matrix. However, for sampling purposes, an upper triangular \mathbf{L} works just as well. It turns out that using an upper triangular \mathbf{L} in the decomposition process leads to a much simpler solution, where all (squared) entries have a simple, closed form expression, and can be easily computed on-line without requiring any preprocessing

computation or storage. (By contrast, numerical computations suggest that the standard Cholesky decomposition with lower triangular \mathbf{L} is far less regular, and even precomputing it requires exponentially higher precision arithmetic than our upper triangular solution.) So, we let \mathbf{L} be an upper triangular matrix, and set $r = b + 1$.

For any r , the perturbation's covariance matrix $\Sigma_2 = r^2\mathbf{I} - \Sigma_1$ has Cholesky decomposition $\Sigma_2 = \mathbf{L} \cdot \mathbf{L}^T$ where \mathbf{L} is the sparse upper triangular matrix defined by the following equations:

$$\mathbf{L} = \begin{bmatrix} l_0 & h_1 & & & & \\ & l_1 & h_2 & & & \\ & & \ddots & \ddots & & \\ & & & \ddots & \ddots & \\ & & & & h_{k-1} & \\ & & & & & l_{k-1} \end{bmatrix} \quad \text{where} \quad \begin{aligned} l_0^2 + h_1^2 &= r^2 - b^2 \\ l_i^2 + h_{i+1}^2 &= r^2 - (b^2 + 1) \quad (i = 1, \dots, k-2) \\ l_{k-1}^2 &= r^2 - (b^2 + 1) \\ l_i h_i &= b \quad (i = 1, \dots, k-1) \end{aligned}$$

It can be easily verified that these equations have the following simple closed form solution:

$$r = b + 1, \quad l_0^2 = b \left(1 + \frac{1}{k}\right) + 1, \quad l_i^2 = b \left(1 + \frac{1}{k-i}\right), \quad h_{i+1}^2 = b \left(1 - \frac{1}{k-i}\right) \quad (1)$$

We observe that also the inverse transformation $\mathbf{B}_{b^k}^{-1}$ has a simple, closed-form solution: the i th column of $\mathbf{B}_{b^k}^{-1}$ equals $(0, \dots, 0, \frac{1}{b}, \dots, (\frac{1}{b})^{k-i})$. Notice that this matrix is not sparse, as it has $O(k^2)$ nonzero entries. However, there is no need to store it and the associated transformation can still be computed in linear time by solving the sparse triangular system $\mathbf{T}\mathbf{x} = \mathbf{b}$ by back-substitution.

3.2 The Algorithm

The sampling algorithm, SAMPLEG, is shown in Figure 2. It takes as input a modulus q , an integer variance s , a coset u of $\Lambda^\perp(\mathbf{g}^T)$, and outputs a sample statistically close to $D_{\Lambda_u^\perp(\mathbf{g}^T), s}$. SAMPLEG relies on subroutines PERTURB and SAMPLED where PERTURB(σ) returns a perturbation, \mathbf{p} , statistically close to $D_{\mathcal{L}(\Sigma_2), \sigma \cdot \sqrt{\Sigma_2}}$, and SAMPLED(σ, \mathbf{c}) returns a sample \mathbf{z} such that $\mathbf{D}\mathbf{z}$ is statistically close to $D_{\mathcal{L}(\mathbf{D}), -\mathbf{c}, \sigma}$. Both PERTURB and SAMPLED are instantiations of the randomized nearest plane algorithm [36, 28]. In addition, PERTURB and SAMPLED rely on a subroutine SAMPLEZ(σ, t) which returns a sample statistically close to $D_{\mathbb{Z}, t, \sigma}$.

Assuming constant time sampling for SAMPLEZ and scalar arithmetic, SAMPLEG runs in time $O(k)$. The scalars c_i in SAMPLEG, representing $\mathbf{c} = \mathbf{B}_{b^k}^{-1}(\mathbf{u} - \mathbf{p})$, and d_i in SAMPLED, representing the last column of \mathbf{D} , are rational numbers of the form x/b^i for a small integer x and $i \in [k]$. The numbers l_i, h_i are positive numbers less than $\sqrt{2b+1}$. Though recent results suggests otherwise [52], longer than double floating point precision may be needed for l_i and h_i in applications where $k = O(n)$ instead of $k = O(\log n)$. Then, SAMPLEZ could be instantiated with the lazy floating point techniques of [23] and SAMPLEG would be quasi-linear time in k instead of linear in k .

By combining the bounds in Theorems 2.1 and 3, the variance s can be practically as small as in the case when $q = b^k$. The algorithms store floating point numbers c_i, d_i, h_i , and l_i for a total storage of $O(k)$ floating point numbers, but can be adapted to constant time storage since they are determined by simple recurrence relations (c_i, d_i) or simple formulas (h_i, l_i). We conclude with the statement of correctness in the form of the following corollary.

Corollary 1 *Let $0 < \epsilon \leq 1/2$ be such that $\frac{s^2}{(b+1)^2} \geq \eta_\epsilon(\mathcal{L}(\mathbf{D}))$ and $\sqrt{\Sigma_3} \geq \eta_\epsilon(\mathcal{L}([b+1]^2\mathbf{B}_{b^k}^{-1} - \mathbf{B}_{b^k}^T))$ where $\Sigma_3^{-1} = \frac{(b+1)^2}{s^2}\mathbf{I} + [s^2\mathbf{B}_{b^k}^{-1}\mathbf{B}_{b^k}^{-t} - \frac{s^2}{(b+1)^2}\mathbf{I}]^{-1}$. In addition, let $\frac{s}{b+1} \geq \max\{\|\mathbf{D}\|, \|\mathbf{L}^T\|\} \cdot \omega(\sqrt{\log k})$. Then, SAMPLEG returns a perturbation within a statistical distance $O(\epsilon)$ from $D_{\Lambda_u^\perp(\mathbf{g}^T), s}$ for any $q < b^k$.*

4 Perturbation Sampling in Cyclotomic Rings

The lattice preimage sampling algorithm of [44] requires the generation of $n(2 + \log q)$ -dimensional gaussian perturbation vectors \mathbf{p} with covariance $\Sigma_p = s^2 \cdot \mathbf{I} - \alpha^2 \mathbf{T} \cdot \mathbf{T}^T$ where $\mathbf{T} \in \mathbb{Z}^{(2+\log q)n \times n \log q}$ is a matrix with

SAMPLEG($s, \mathbf{u} = [u]_b^k, \mathbf{q} = [q]_b^k$)

```

 $\sigma := s/(b+1)$ 
 $\mathbf{p} \leftarrow \text{PERTURB}(\sigma)$ 
for  $i = 0, \dots, k-1$  :
     $c_i := (c_{i-1} + u_i - p_i)/b$ 
 $\mathbf{z} \leftarrow \text{SAMPLED}(\sigma, \mathbf{c})$ 
for  $i = 0, \dots, k-2$  :
     $t_i := b \cdot z_i - z_{i-1} + q_i \cdot z_{k-1} + u_i$ 
 $t_{k-1} := q_{k-1} \cdot z_{k-1} - z_{k-2} + u_{k-1}$ 
return  $\mathbf{t}$ 

```

PERTURB(σ)

```

 $\beta := 0$ 
for  $i = 0, \dots, k-1$  :
     $c_i := \beta/l_i$ , and  $\sigma_i := \sigma/l_i$ 
     $z_i \leftarrow \text{SAMPLEZ}(\sigma_i, c_i)$ 
     $\beta := -z_i h_i$ 
 $p_0 := (2b+1)z_0 + bz_1$ 
for  $i := 1, \dots, k-1$  :
     $p_i := b(z_{i-1} + 2z_i + z_{i+1})$ 
return  $\mathbf{p}$ 

```

SAMPLED(σ, \mathbf{c})

```

 $z_{k-1} \leftarrow \text{SAMPLEZ}(\sigma/d_{k-1}, -c_{k-1}/d_{k-1})$ 
 $\mathbf{c} := \mathbf{c} - z_{k-1} \mathbf{d}$ 
for  $i \in \{0, \dots, k-2\}$  :
     $z_i \leftarrow \text{SAMPLEZ}(\sigma, -c_i)$ 
return  $\mathbf{z}$ 

```

Figure 2: Sampling algorithm for G -lattices for any modulus $q < b^k$. The algorithms take b and k as implicit parameters, and SAMPLEG outputs a sample with distribution statistically close to $D_{\Lambda_u^+(\mathbf{g}^T), s}$. Any scalar with an index out of range is 0, i.e. $c_{-1} = z_{-1} = z_k = 0$.

small entries serving as a lattice trapdoor, α is a small constant factor and s is an upper bound on the spectral norm of $\alpha \mathbf{T}$. In [44] this is accomplished using the Cholesky factorization of Σ_p , which takes $O(n \log q)^3$ precomputation and $O(n \log q)^2$ storage and running time. (All integer arithmetics can be performed modulo q , and time and space complexity bounds are in terms of arithmetic operations in \mathbb{Z}_q .)

The trapdoor matrix \mathbf{T} of [44] has some additional structure: $\mathbf{T}^T = [\tilde{\mathbf{T}}^T, \mathbf{I}]$ for some $\tilde{\mathbf{T}} \in \mathbb{Z}^{2n \times n \log q}$. Moreover, when working with algebraic lattices, $\tilde{\mathbf{T}} = \phi_n(\tilde{\mathbf{T}})$ is the image (under a ring embedding $\phi_n: R_n \rightarrow \mathbb{Z}^{n \times n}$) of some matrix $\tilde{\mathbf{T}} \in R_n^{2 \times \log q}$ with entries in a ring R_n of rank n . (Most commonly, $R_n = \mathcal{O}_{2n} = \mathbb{Z}[x]/(x^n + 1)$ is the ring of integers of the $(2n)$ th cyclotomic field \mathcal{K}_{2n} for $n = 2^k$ a power of two.) In [7] it is observed that, using the sparsity of Σ_p , the preprocessing storage and on-line computation cost of noise perturbation reduce to $O(n^2 \log q)$.⁴ This is a factor $\log q$ improvement over a generic implementation, but it is still quadratic in the main security parameter n . This can be a significant improvement in practice, but the overall cost of the algorithm remains substantial. When using generic trapdoors $\tilde{\mathbf{T}} \in \mathbb{Z}^{2n \times n \log q}$, there is little hope to improve the running time below $O(n^2 \log q)$, because just reading the matrix $\tilde{\mathbf{T}}$ takes this much time. However, when using algebraic lattices, the trapdoor $\tilde{\mathbf{T}} = \phi_n(\tilde{\mathbf{T}})$ admits a compact representation $\tilde{\mathbf{T}}$ consisting of only $2n \log q$ integers, so one may hope to reduce the running time to linear or quasi-linear in n . Unfortunately, all efficiency advantages of working with structured lattices are lost when computing the Cholesky decomposition of Σ_p as suggested in [44], because the Cholesky decomposition does not respect the ring structure and produces arbitrary matrices over \mathbb{R} .

A method for discrete gaussian sampling with covariance described by a ring element R_n in quasi-linear time is given in [23]. A similar quasi-linear sampler can also be obtained by using the CRT transformation (see [42]) to diagonalize the matrix described by the ring element. Both methods produce gaussian vectors with arbitrary real coordinates, and require the use of the randomized rounding sampler of [48] to map the result to an integer vector. In this section we give an alternative, more direct algorithm to generate integer perturbation vectors \mathbf{p} with covariance Σ_p when $\tilde{\mathbf{T}} = \phi_n(\tilde{\mathbf{T}})$. Our algorithm takes full advantage of the ring structure of R_n , compactly representing Σ_p and all other matrices generated during the execution of the algorithm as the image of matrices with entries in the ring R_n . In particular, similarly to [23], our

⁴Sparsity also reduces the preprocessing running time to $O(\log q \cdot n^2 + n^3) = O(n^3)$, but still cubic in n .

<pre> SAMPLEP($n, q, s^2, \alpha^2, \tilde{\mathbf{T}}$) $z = (\alpha^{-2} - s^{-2})^{-1}$ $a = s^2 - z \cdot \tilde{\mathbf{T}}_0 \tilde{\mathbf{T}}_0^T$ $b = -z \cdot \tilde{\mathbf{T}}_0 \tilde{\mathbf{T}}_1^T$ $d = s^2 - z \cdot \tilde{\mathbf{T}}_1 \tilde{\mathbf{T}}_1^T$ for $i = 0, \dots, (n \log q - 1)$: $\mathbf{q}_i \leftarrow \text{SAMPLER}(s^2 - \alpha^2)$ $\mathbf{p} \leftarrow \text{SAMPLE2}(a, b, d)$ return $\left(\mathbf{p} - \left(\frac{\alpha}{s^2 - \alpha^2} \right) \mathbf{T} \mathbf{q}, \mathbf{q} \right)$ </pre>	<pre> SAMPLE2(a, b, d) $p_1 \leftarrow \text{SAMPLEF}(d)$ $p_0 \leftarrow \text{SAMPLEF}(a - bd^{-1}b^*)$ return $(p_0 + (bd^{-1})p_1, p_1)$ SAMPLEF(f) if $\dim(f) = 1$ return $\text{SAMPLER}(f)$ else let $f(x) = f_0(x^2) + x \cdot f_1(x^2)$ $(p_0, p_1) \leftarrow \text{SAMPLE2}(f_0, f_1, f_0)$ let $p(x) = p_0(x^2) + x \cdot p_1(x^2)$ return p </pre>
--	--

Figure 3: Sampling algorithm SAMPLEP for floating point perturbations where $\mathbf{T} = \phi_n(\tilde{\mathbf{T}})$ is a compact trapdoor over a power of two cyclotomic ring. Note, $\tilde{\mathbf{T}}_i$ is a row vector over R_n for each $i \in \{0, 1\}$. The algorithm uses a subroutine SAMPLER(σ^2) to sample a 1-dimensional gaussian with variance σ^2 centered at 0.

algorithm has time and space complexity quasi-linear in n , but it does not require any preprocessing/storage, or postprocessing for rounding the result to an integer vector. The algorithm can be expressed in a modular way as the combination of three steps:

1. First, the problem of sampling a $O(n \log q)$ -dimensional integer vectors \mathbf{p} with covariance Σ_p is reduced to the problem of sampling a $2n$ -dimensional integer vector with covariance expressed by a 2×2 matrix over R_n .
2. Next, the problem of sampling with covariance in $R_n^{2 \times 2}$ is reduced to sampling two n -dimensional vectors, each with a covariance expressed by a single ring element in R_n .
3. Finally, if $n > 1$, the sampling problem with covariance in R_n is reduced to sampling an n -dimensional perturbation with covariance expressed by a 2×2 matrix over the smaller ring $R_{n/2}$.

Iterating the last two steps $\log n$ times reduces the original problem to sampling in $R_1 = \mathbb{Z}$. Details about each step are given in the next subsections. We remark that the algorithm is described as a recursive procedure only for simplicity of presentation and analysis, and it can be implemented just as easily using a simple nested loop, similarly to many FFT-like algorithms. We first describe an algorithm to generate perturbations from continuous gaussians, which admits a simpler proof, but requires the use of high precision floating point arithmetics. Then, we describe an integer-based version of the algorithm which directly generates perturbations from discrete gaussians over $\mathbb{Z}^{n(2+\log q)}$. The continuous gaussian perturbation generation method presented here is given primarily as a warm up to the main algorithm to generate discrete gaussian perturbations.

4.1 Algorithm for Floating Point Perturbations

The sampling algorithm for continuous gaussians is shown in Figure 3. The entry point of the algorithm is the SAMPLEP procedure, which takes as input integer parameters n, q , a matrix $\tilde{\mathbf{T}} \in R_n^{2 \times \log q}$ and two positive real numbers s^2, α^2 , and is expected to produce an $n(2 + \log q)$ -dimensional vector \mathbf{p} with (non-spherical) gaussian distribution $\mathcal{D}_{\sqrt{\Sigma_p}}$ of covariance

$$\Sigma_p = s^2 \cdot \mathbf{I} - \alpha^2 \begin{bmatrix} \phi_n(\tilde{\mathbf{T}}) \\ \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \phi_n(\tilde{\mathbf{T}})^T & \mathbf{I} \end{bmatrix} = \begin{bmatrix} s^2 \mathbf{I} - \alpha^2 \phi_n(\tilde{\mathbf{T}}) \cdot \phi_n(\tilde{\mathbf{T}})^T & -\alpha^2 \phi_n(\tilde{\mathbf{T}}) \\ -\alpha^2 \phi_n(\tilde{\mathbf{T}})^T & (s^2 - \alpha^2) \mathbf{I} \end{bmatrix} \quad (2)$$

The algorithm calls two subroutines:

- $\text{SAMPLER}(s^2 - \alpha^2)$ which samples a one-dimensional gaussian variable of covariance $s^2 - \alpha^2$, and can be implemented using any standard technique, and
- $\text{SAMPLE2}(a, b, d)$, which, on input three ring elements a, b, d compactly describing a positive definite matrix

$$\Sigma_2 = \begin{bmatrix} \phi_n(a) & \phi_n(b) \\ \phi_n(b)^T & \phi_n(d) \end{bmatrix},$$

is expected to sample a $(2n)$ -dimensional vector $p \leftarrow D_{\sqrt{\Sigma_2}}$ with covariance Σ_2 .

In turns, SAMPLE2 (also described in Figure 3) makes use of a procedure $\text{SAMPLEF}(f)$ which on input a ring element f with positive definite $\phi_n(f)$, returns a sample $p \leftarrow D_{\sqrt{\phi_n(f)}}$.

Correctness The proof of correctness of the algorithm is based on the following general lemma.

Lemma 4.1 For any positive definite matrix $\Sigma = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{D} \end{bmatrix}$, the process

1. $\mathbf{p}_1 \leftarrow D_{\sqrt{\mathbf{A} - \mathbf{B}\mathbf{D}^{-1}\mathbf{B}^T}}$
2. $\mathbf{p}_2 \leftarrow D_{\sqrt{\mathbf{D}}}$
3. return $\begin{bmatrix} \mathbf{B}\mathbf{D}^{-1} \\ \mathbf{I} \end{bmatrix} \mathbf{p}_2 + \begin{bmatrix} \mathbf{I} \\ \mathbf{0} \end{bmatrix} \mathbf{p}_1$

produces a vector with gaussian distribution $D_{\sqrt{\Sigma}}$.

Proof Let $\mathbf{p}_2, \mathbf{p}_1$ be independent $\mathbf{0}$ -mean multivariate gaussian samples with respective covariances \mathbf{D} and $\mathbf{A} - \mathbf{B}\mathbf{D}^{-1}\mathbf{B}^T$. Due to independence, the output $(\mathbf{B}\mathbf{D}^{-1}\mathbf{p}_2 + \mathbf{p}_1, \mathbf{p}_2)$ is gaussian with covariance

$$\begin{bmatrix} \mathbf{B}\mathbf{D}^{-1} \\ \mathbf{I} \end{bmatrix} \mathbf{D} \begin{bmatrix} \mathbf{D}^{-T}\mathbf{B}^T & \mathbf{I} \end{bmatrix} + \begin{bmatrix} \mathbf{I} \\ \mathbf{0} \end{bmatrix} (\mathbf{A} - \mathbf{B}\mathbf{D}^{-1}\mathbf{B}^T) \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{D} \end{bmatrix}$$

as claimed. \square

Consider the ring \mathcal{O}_{2n} as a two-dimensional free \mathcal{O}_n -module (as well as \mathcal{K}_{2n} as a two dimensional \mathcal{K}_n -vector space) by splitting a polynomial $f(x) \in \mathcal{K}_{2n}$ into $f(x) = f_0(x^2) + x \cdot f_1(x^2)$ for $f_i \in \mathcal{K}_n$. Algebraically, this is seen by viewing \mathcal{K}_{2n} under the isomorphism $\mathcal{K}_{2n} = \mathbb{Q}[x]/(x^{2n} + 1) \cong \mathbb{Q}(\zeta_{2n})$ ($x \mapsto \zeta_{2n}$) with the relation $\zeta_{2n}^2 = \zeta_n$ for primitive n -th and $2n$ -th roots of unity ζ_n and ζ_{2n} , respectively.

Now, the (power basis) multiplication matrix of a field element can be represented as a two-by-two block matrix with multiplication matrices in the smaller field, $\phi_{n/2}(\cdot)$, as blocks by permuting the row and column indices according to the stride permutation as in the FFT (permuting the increasing elements of $[n]$ to the increasing evens followed by the increasing odds). Specifically, we have the following relation after the permutation

$$\phi_n(f) = \begin{bmatrix} \phi_{n/2}(f_0) & \phi_{n/2}(x \cdot f_1) \\ \phi_{n/2}(f_1) & \phi_{n/2}(f_0) \end{bmatrix}.$$

Notice, $\phi_{n/2}(x \cdot f_1) = \phi_{n/2}(f_1)^T = \phi_{n/2}(f_1^*)$ when $\phi_n \succ 0$ as is the case for the input f . Now, SAMPLEF can simply perform the convolution in Lemma 4.1 with a call to SAMPLE2 when the dimension is greater than one and sampling $D_{\sqrt{f}}$ otherwise.

We prove the correctness of the sampling algorithm in three steps, corresponding to the three procedures SAMPLEP , SAMPLE2 and SAMPLEF .

Corollary 2 If SAMPLEF correctly samples the distribution $D_{\sqrt{\phi_n(f)}}$, then SAMPLE2 correctly samples the distribution $D_{\sqrt{\Sigma_2}}$.

```

SAMPLEPZ( $n, q, s, \alpha, \tilde{\mathbf{T}}$ )
   $z = (\alpha^{-2} - s^{-2})^{-1}$ 
   $a := s^2 - z \tilde{\mathbf{T}}_0 \tilde{\mathbf{T}}_0^T$ 
   $b := -z \tilde{\mathbf{T}}_0 \tilde{\mathbf{T}}_1^T$ 
   $d := s^2 - z \tilde{\mathbf{T}}_1 \tilde{\mathbf{T}}_1^T$ 

  for  $i = 0, \dots, (n \log q - 1)$  :
     $q_i \leftarrow \text{SAMPLEZ}(s^2 - \alpha^2)$ 
   $\mathbf{c} := -\frac{\alpha^2}{s^2 - \alpha^2} \tilde{\mathbf{T}} \mathbf{q}$ 
   $\mathbf{p} \leftarrow \text{SAMPLE2Z}(a, b, d, \mathbf{c})$ 
  return ( $\mathbf{p}, \mathbf{q}$ )

SAMPLE2Z( $a, b, d, \mathbf{c}$ )
  let  $\mathbf{c} = (c_0, c_1)$ 
   $q_1 \leftarrow \text{SAMPLEFZ}(d, c_1)$ 
   $c_0 := c_0 + b d^{-1} (q_1 - c_1)$ 
   $q_0 \leftarrow \text{SAMPLEFZ}(a - b d^{-1} b^*, c_0)$ 
  return ( $q_0, q_1$ )

SAMPLEFZ( $f, \mathbf{c}$ )
  if  $\dim(f) = 1$  return  $\text{SAMPLEZ}(f, \mathbf{c})$ 
  else let  $f(x) = f_0(x^2) + x \cdot f_1(x^2)$ 
     $\mathbf{c}' := P_{\text{stride}(n)}(\mathbf{c})$ 
    ( $q_0, q_1$ )  $\leftarrow \text{SAMPLE2Z}(f_0, f_1, f_0, \mathbf{c}')$ 
    let  $q(x) = q_0(x^2) + x \cdot q_1(x^2)$ 
    return  $q$ 

```

Figure 4: Sampling algorithm SAMPLEPZ for integer perturbations where $\mathbf{T} = \phi_n(\tilde{\mathbf{T}})$ is a compact trapdoor over a power of two cyclotomic ring. Note, $\tilde{\mathbf{T}}_i$ is a row vector over R_n for each $i \in \{0, 1\}$. The algorithm uses a subroutine SAMPLEZ(σ^2, t) which samples a discrete gaussian over \mathbb{Z} with variance σ^2 centered at t . The stride permutation, $P_{\text{stride}(n)}$, sends a vector of coefficients to the increasing even indices followed by the increasing odd indices.

Proof The corollary follows by instantiating Lemma 4.1 with $\mathbf{A} = \phi_n(a)$, $\mathbf{B} = \phi_n(b)$ and $\mathbf{D} = \phi_n(d)$. \square

Corollary 3 *If SAMPLE2 correctly samples the distribution $D_{\sqrt{\Sigma_2}}$, then SAMPLEP correctly samples the distribution $D_{\sqrt{\Sigma_p}}$.*

Proof The corollary follows by instantiating Lemma 4.1 with $\Sigma := \Sigma_p$, equivalently $\mathbf{A} = s^2 \mathbf{I} - \alpha^2 \phi_n(\tilde{\mathbf{T}}) \cdot \phi_n(\tilde{\mathbf{T}})^T$, $\mathbf{B} = -\alpha^2 \phi_n(\tilde{\mathbf{T}})$ and $\mathbf{D} = (s^2 - \alpha^2) \mathbf{I}$. \square

Efficiency Multiplications are done in the field \mathcal{K}_i , for an element's dimension $i \in \{1, 2, \dots, 2n\}$, in time $\tilde{O}(i)$ by using the Chinese remainder transform (CRT) [42].

By treating scalar arithmetic as constant time, SAMPLEF has a time complexity of $\tilde{O}(n \log q)$ for the transformation by \mathbf{T} is $O(n \log n \log q)$ and SAMPLEF has complexity $O(n \log^2 n)$ (represented by the recurrence $R(n) = 2R(n/2) + (n/2) \log n/2$). The algorithm requires $n \log q$ scalar storage for the trapdoor $\tilde{\mathbf{T}}$.

4.2 Integer Perturbation Algorithm for Power of Two Cyclotomics

In this subsection we present a discrete version of the SAMPLEP algorithm which produces $n(2 + \log q)$ -dimensional perturbations $\mathbf{p} \sim D_{\mathbb{Z}^{n(2+\log q)}, \sqrt{\Sigma_p}}$ from a discrete gaussian in time $\tilde{O}(n \log q)$. The main algorithm SAMPLEPZ (and auxiliary algorithms SAMPLE2Z, SAMPLEFZ) are described in Figure 4, and closely follow their continuous counterparts from Figure 3. We refer the reader to Subsection 4.1 for a discussion of the intuition behind the algorithms, and move straight to their formal analysis.

Correctness We will use the following lemma for the correctness proof. It states that if a discrete gaussian on the integer lattice is wide enough, then the lower dimensional discrete gaussians with covariance that is a principle submatrix of the original is wide enough on its respective integer sublattice.

Lemma 4.2 Let, $\epsilon > 0$, $\Sigma \succ 0$ be a positive definite matrix in $\mathbb{R}^{n \times n}$, λ_{\min} be its minimum eigenvalue, and let $I_0, I_1 \subset [n]$ be arbitrary, non-empty subsets. If $\sqrt{\lambda_{\min}} \geq \eta_\epsilon(\mathbb{Z}^n)$, then $\sqrt{\Sigma[I_0]} \geq \eta_\epsilon(\mathbb{Z}^{|I_0|})$ and $\sqrt{\Sigma/\bar{I}_1} \geq \eta_\epsilon(\mathbb{Z}^{n-|I_1|})$ for any principal submatrix - Schur complement pair, $(\Sigma[I_0], \Sigma/\bar{I}_1)$, of Σ .

Proof Let $\mathbf{M} := \Sigma[I_0] \in \mathbb{R}^{n_0 \times n_0}$ for $n_0 = |I_0|$. \mathbf{M} is diagonalizable so let $\mathbf{M} = \mathbf{Q}^T \mathbf{\Lambda} \mathbf{Q}$ be its diagonalization. Notice, we have the following inequality from the interlacing theorems

$$\mathbf{x}^T \mathbf{M} \mathbf{x} = \mathbf{x}^T \mathbf{Q}^T \mathbf{\Lambda} \mathbf{Q} \mathbf{x} = \mathbf{y}^T \mathbf{\Lambda} \mathbf{y} = \sum_{i \in [n_0]} \lambda_i y_i^2 \geq \lambda_{\min} \|\mathbf{y}\|^2 = \lambda_{\min} \|\mathbf{x}\|^2.$$

Next, we can bound the quantity $\rho_{\mathbf{M}^{-1}(\mathbb{Z}^{(n_0)^*} \setminus \{\mathbf{0}\})} = \rho_{\mathbf{M}^{-1}(\mathbb{Z}^{n_0} \setminus \{\mathbf{0}\})}$ by ϵ :

$$\rho_{\mathbf{M}^{-1}(\mathbb{Z}^{n_0} \setminus \{\mathbf{0}\})} = \sum_{\mathbf{x} \in \mathbb{Z}^{n_0} \setminus \{\mathbf{0}\}} e^{-\pi \mathbf{x}^T \mathbf{M} \mathbf{x}} \leq \sum_{\mathbf{x} \in \mathbb{Z}^{n_0} \setminus \{\mathbf{0}\}} e^{-\pi \lambda_{\min} \|\mathbf{x}\|^2} \leq \sum_{\mathbf{x} \in \mathbb{Z}^{n_0} \setminus \{\mathbf{0}\}} e^{-\pi \lambda_{\min} \|\mathbf{x}\|^2} \leq \epsilon.$$

The jump from \mathbb{Z}^{n_0} to \mathbb{Z}^n comes from the relation $\mathbb{Z}^{n_0} \subset \mathbb{Z}^n$. The proof for the Schur complement is identical. \square

Next, we state an analogous lemma for discrete gaussians to Lemma 4.1.

Lemma 4.3 For any real $0 < \epsilon \leq 1/4$, positive integers n, m , positive definite matrix $\Sigma = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^T & \mathbf{D} \end{bmatrix}$ with $\sqrt{\Sigma} \geq \eta_\epsilon(\mathbb{Z}^{n+m})$, $\det(\Sigma/\mathbf{D}) > 1$, $\mathbf{A} \in \mathbb{Z}^{n \times n}$, $\mathbf{B} \in \mathbb{Z}^{n \times m}$, $\mathbf{D} \in \mathbb{Z}^{m \times m}$, and vector $\mathbf{c} = (\mathbf{c}_1, \mathbf{c}_2) \in \mathbb{R}^{n+m}$, the random process

- $\mathbf{x}_2 \leftarrow D_{\mathbb{Z}^m, \sqrt{\mathbf{D}}, \mathbf{c}_2}$.
- $\mathbf{x}_1 \leftarrow D_{\mathbb{Z}^n, \sqrt{\mathbf{A} - \mathbf{B}\mathbf{D}^{-1}\mathbf{B}^T}, \mathbf{c}_1 + \mathbf{B}\mathbf{D}^{-1}(\mathbf{x}_2 - \mathbf{c}_2)}$.

produces a vector $(\mathbf{x}_1, \mathbf{x}_2) \in \mathbb{Z}^{n+m}$ distributed within statistical distance 6ϵ from $D_{\mathbb{Z}^{n+m}, \sqrt{\Sigma}, \mathbf{c}}$. In particular, the probability of each point $(\bar{\mathbf{x}}_1, \bar{\mathbf{x}}_2) \in \mathbb{Z}^{n+m}$ is in the interval $[1 - 12\epsilon, 1 + 12\epsilon] \cdot D_{\mathbb{Z}^{n+m}, \sqrt{\Sigma}, \mathbf{c}}(\bar{\mathbf{x}}_1, \bar{\mathbf{x}}_2)$.

Proof (Sketch)

$$\begin{aligned} \Pr[\mathbf{x}_1 = \bar{\mathbf{x}}_1, \mathbf{x}_2 = \bar{\mathbf{x}}_2] &= \frac{\rho_{\sqrt{\Sigma/\mathbf{D}}}(\bar{\mathbf{x}}_1 - \mathbf{c}_1 - \mathbf{B}\mathbf{D}^{-1}(\bar{\mathbf{x}}_2 - \mathbf{c}_2)) \cdot \rho_{\sqrt{\mathbf{D}}}(\bar{\mathbf{x}}_2 - \mathbf{c}_2)}{\rho_{\sqrt{\Sigma/\mathbf{D}}}(\mathbb{Z}^n - \mathbf{c}_1 - \mathbf{B}\mathbf{D}^{-1}(\bar{\mathbf{x}}_2 - \mathbf{c}_2)) \cdot \rho_{\sqrt{\mathbf{D}}}(\mathbb{Z}^m - \mathbf{c}_2)} \\ &\in D_{\mathbb{Z}^{n+m}, \sqrt{\Sigma}, \mathbf{c}} \cdot \left(1 \pm 2\epsilon \frac{\rho_{\sqrt{\mathbf{D}}}(\mathbb{Z}^m - \mathbf{c}_2)}{\rho_{\sqrt{\Sigma}}(\mathbb{Z}^{n+m} - \mathbf{c})} \right)^{-1} \end{aligned}$$

The first equation is from construction, and the second equation is a combination of Lemma 2.2 and the formula of the inverse of a block matrix. Next, apply Lemma 2.2 again, which we can do because of Lemma 4.2, to yield the interval with centered gaussian sums. We know $\frac{\rho_{\sqrt{\mathbf{D}}}(\mathbb{Z}^m)}{\rho_{\sqrt{\Sigma}}(\mathbb{Z}^{n+m})} < 1$ by applying the Poisson summation formula to the both the numerator and denominator, using $\det(\Sigma/\mathbf{D}) > 1$, then treating \mathbb{Z}^m as a strict subset of \mathbb{Z}^{n+m} . We also used $\det \Sigma = \det \Sigma/\mathbf{D} \cdot \det \mathbf{D}$. Finally, we have the following when $\epsilon \in (0, 1/4)$:

$$\Pr[\mathbf{x}_1 = \bar{\mathbf{x}}_1, \mathbf{x}_2 = \bar{\mathbf{x}}_2] \in [1 - 12\epsilon, 1 + 12\epsilon] \cdot D_{\mathbb{Z}^{n+m}, \sqrt{\Sigma}, \mathbf{c}}$$

\square

We need to ensure each discrete gaussian convolution in the algorithm is non-degenerate. The fact that $\Sigma_p \succ 0$ is enough for the continuous algorithms to return a non-degenerate sample, though not for the discrete case. As shown in Lemma 4.3, we need $\Sigma \geq \eta_\epsilon(\mathbb{Z}^{n'})$ at each of the $O(n)$ discrete gaussian convolutions.

We now show the correctness of SAMPLEFZ implies the correctness of SAMPLE2Z, and the correctness of SAMPLE2Z implies the correctness of SAMPLEPZ.

Corollary 4 *If SAMPLEFZ correctly samples the distribution $D_{\mathbb{Z}^{n'}, \sqrt{\phi_{n'}(f)}, \mathbf{c}}$ for $n' \in 1, 2, \dots, n$ and $\sqrt{\Sigma_2} \geq \eta_\epsilon(\mathbb{Z}^{2n'})$, then SAMPLE2Z samples from a distribution within a statistical distance of 6ϵ of $D_{\mathbb{Z}^{2n'}, \sqrt{\Sigma_2}, \mathbf{c}}$ for any real $0 < \epsilon \leq 1/4$.*

Proof The corollary follows by instantiating Lemma 4.3 with $\mathbf{A} = \phi_n(a)$, $\mathbf{B} = \phi_n(b)$ and $\mathbf{D} = \phi_n(d)$. \square

Corollary 4 shows the correctness of SAMPLEFZ as well since we can follow the recursions to the base case, the one-dimensional sampler, which we assume is error-less.

Corollary 5 *If SAMPLE2Z correctly samples the distribution $D_{\mathbb{Z}^{2n'}, \sqrt{\Sigma_2}, \mathbf{c}}$ and $\sqrt{\Sigma_p} \geq \eta_\epsilon(\mathbb{Z}^{n(2+\log q)})$, then SAMPLEPZ returns a sample within a statistical distance of 6ϵ of the distribution $D_{\mathbb{Z}^{n(2+\log q)}, \sqrt{\Sigma_p}}$ for any real $0 < \epsilon \leq 1/4$.*

Proof The corollary follows by instantiating Lemma 4.3 with $\Sigma := \Sigma_p$, equivalently

$\mathbf{A} = s^2\mathbf{I} - \alpha^2\phi_n(\tilde{\mathbf{T}}) \cdot \phi_n(\tilde{\mathbf{T}})^T$, $\mathbf{B} = -\alpha^2\phi_n(\tilde{\mathbf{T}})$ and $\mathbf{D} = (s^2 - \alpha^2)\mathbf{I}$. \square

Finally, we bound the statistical distance between the output of SAMPLEPZ and the desired distribution.

Theorem 4 *Let $0 < \epsilon \leq 1/4$ and $\lambda_{\min} > 1$ be the minimum eigenvalue of Σ_p . If $\lambda_{\min} \geq \eta_\epsilon(\mathbb{Z}^{n(2+\log q)})$, then SAMPLEPZ returns a perturbation within a statistical distance $O(n \cdot \epsilon)$ of $D_{\mathbb{Z}^{n(2+\log q)}, \sqrt{\Sigma_p}}$.*

Proof The interlacing theorems and Lemma 4.2 imply the conditions for Corollaries 4 and 5 are met. Since there are $\Theta(n)$ convolutions, the output of SAMPLEPZ is in the interval $[(1-12\epsilon)^{O(n)}, (1+12\epsilon)^{O(n)}]D_{\mathbb{Z}^{n(2+\log q)}, \sqrt{\Sigma_p}}$ and the statistical distance is within $O(n\epsilon)$ by the binomial theorem and ignoring non-linear factors in ϵ . \square

Storage and Precision Next, we bound the magnitude of the centers and variances given to the sampler SAMPLEZ. The one-dimensional variances are bounded by the interlacing theorems since they are computed from a sequence of principal submatrices and their Schur complements from Σ_2 . This shows that the variances f are all bounded by the maximum eigenvalue of Σ_2 , λ_{\max} . Regarding the centers, we assume all one-dimensional \mathbb{Z} -samples are within a distance of $f\sqrt{n}$ (f is the one-dimensional variance) of their centers since each is not with probability $O(2^{-n})$ if SAMPLEZ is a rejection sampler ([28] Lemma 4.2). In addition, one can show that the largest eigenvalue of $\phi_n(bd^{-1})$ is upper-bounded in magnitude by $\lambda_{\max}/\lambda_{\min}$ by the interlacing theorems as well as simultaneous diagonalization of anti-cyclic matrices. This implies each one dimensional center c is upper-bounded in magnitude by $n(\log n)\lambda_{\max}^2/\lambda_{\min} = \tilde{O}(n\lambda_{\max})$ with all but probability $O(2^{-n+\log n})$ when the ratio of the maximum and minimum eigenvalue of Σ_2 is constant.

Representing the rationals as fractions requires bit-length $n \log q$ integers due to the blow-up of numerators and denominators from the inverse ring elements b^{-1} (this can be seen through Cramer's rule). As a result, one should use floating point numbers to represent the centers and covariances.

Assuming constant time for floating point arithmetic and SAMPLEZ, SAMPLEFZ runs in time $\tilde{O}(n)$, like the continuous case in the previous subsection. Therefore, SAMPLEPZ runs in time $\tilde{O}(n \log q)$. Storage consists of reading the trapdoor $\tilde{\mathbf{T}}$ which consists of $2n \log q$ small integers, then the algorithm stores $4n$ floating point numbers for the input of SAMPLE2Z.

Recent results suggest double precision floating point numbers are enough to preserve security in lattice-based cryptosystems [46, 52], but one can use the lazy floating techniques of [23] for SAMPLEZ and still yield a version of SAMPLEPZ that has quasi-linear time complexity on average if longer floating point precision is needed. This would involve tweaking SAMPLEFZ to record its path through the tree of recursions and pass its path to SAMPLEZ. Then, SAMPLEZ could re-compute its center and variance in high precision with access to previous samples and the trapdoor $\tilde{\mathbf{T}}$.

Efficiency Assuming constant time for scalar computations (double precision), SAMPLEPZ runs in time $\tilde{O}(n \log q)$ since it has the same complexity as SAMPLEP in the previous subsection.

4.3 General Cyclotomic Rings

In this subsection, we show the techniques from the power of two cyclotomic case apply to the arbitrary cyclotomic case. Let $n = \varphi(n')$, q be a positive integer, $\mathcal{O}_{n'} = \mathbb{Z}[x]/(\Phi_{n'}(x))$ be the n' -th cyclotomic ring with $\mathcal{K}_{n'}$ as the n' -th cyclotomic field over \mathbb{Q} , and let $\tilde{\mathbf{T}} \in \mathcal{O}_{n'}^{2 \times \log q}$ be a ring trapdoor matrix. Note, the ring $\mathcal{O}_{n'}$ is a lattice in the canonical embedding. Let $\text{rad}(n')$ be the product of all distinct prime divisors of n' . Define the diagonal matrix of a field element, $f \in \mathcal{K}_{n'}$, as $\Psi(f)_{i,i} = f(\zeta^i)$ where ζ is a complex primitive n' -th root of unity and each i is a distinct element in the group of units modulo n' , $i \in \mathbb{Z}_{n'}^*$. This is the multiplication matrix of an element in the canonical embedding. Notice, $\Psi(f)^\dagger = \Psi(f^*)$ since conjugation is an automorphism of all cyclotomic fields over \mathbb{Q} . We apply $\Psi(\cdot)$ element-wise to vectors and matrices over $\mathcal{K}_{n'}$.

Now, our goal is to efficiently sample the lattice $D_{\mathcal{O}_{n'}^{2+\log q}, \sqrt{\Sigma_p}}$ where

$$\Sigma_p = s^2 \mathbf{I} - \alpha^2 \begin{bmatrix} \Psi(\tilde{\mathbf{T}}) \\ I \end{bmatrix} \begin{bmatrix} \Psi(\tilde{\mathbf{T}})^\dagger & I \end{bmatrix}$$

and $\Psi(\tilde{\mathbf{T}})^\dagger$ is the Hermitian transpose of $\Psi(\tilde{\mathbf{T}})$. Sampling $D_{\mathcal{O}_{n'}^{2+\log q}, \sqrt{\Sigma_p}}$ reduces to sampling discrete gaussians over \mathbb{Z} in nearly the same steps as the previous subsection with $z = (\alpha^{-2} - s^{-2})^{-1}$:

1. Sampling $\mathbf{p} \leftarrow D_{\mathcal{O}_{n'}^{2+\log q}, \sqrt{\Sigma_p}}$ reduces to sampling $D_{\mathcal{O}_{n'}^2, \sqrt{\Sigma_{2 \times 2}}}$ where

$$\Sigma_{2 \times 2} = s^2 \mathbf{I} - z \cdot \Psi(\tilde{\mathbf{T}}) \Psi(\tilde{\mathbf{T}})^\dagger = \begin{bmatrix} \Psi(a) & \Psi(b) \\ \Psi(b^*) & \Psi(d) \end{bmatrix}$$

by first sampling $\mathbf{p}_2 \leftarrow D_{\mathcal{O}_{n'}^{\log q}, \sqrt{s^2 - \alpha^2}}$, updating the randomized center $\mathbf{c} := \frac{-\alpha^2}{s^2 - \alpha^2} \Psi(\tilde{\mathbf{T}}) \mathbf{p}_2$, then sampling $\mathbf{p}_1 \leftarrow D_{\mathcal{O}_{n'}^2, \mathbf{c}, \sqrt{\Sigma_{2 \times 2}}}$.

2. Sampling $D_{\mathcal{O}_{n'}^2, \mathbf{c}, \sqrt{\Sigma_{2 \times 2}}}$ reduces to sampling $D_{\mathcal{O}_{n'}, \sqrt{\Psi(f)}}$ for a positive definite field element f by sampling $\mathbf{q}_2 \leftarrow D_{\mathcal{O}_{n'}, \mathbf{c}_2, \sqrt{\Psi(d)}}$, then by updating the center $\mathbf{c}_1 := \mathbf{c}_1 + \Psi(bd^{-1})(\mathbf{q}_2 - \mathbf{c}_2)$ and sampling $\mathbf{q}_1 \leftarrow D_{\mathcal{O}_{n'}, \mathbf{c}_1, \sqrt{\Psi(a - bd^{-1}b^*)}}$.

Similar to how SAMPLEPZ must sample $D_{\mathbb{Z}^{n \log q}, \sqrt{s^2 - \alpha^2}}$, the first step above requires sampling the discrete gaussian $D_{\mathcal{O}_{n'}^{\log q}, \sqrt{s^2 - \alpha^2}}$. This can be done in $O(\text{rad}(n') n' \log q)$ since spherical discrete gaussians over the ring $\mathcal{O}_{n'}$ can be sampled in time $O(\text{rad}(n') n')$ [42].

By using the randomized nearest plane algorithm to sample discrete gaussians on $\mathcal{O}_{n'}$ with diagonal covariances, sampling \mathbf{p} statistically close to $D_{\mathcal{O}_{n'}^{2+\log q}, \sqrt{\Sigma_p}}$ is $O(\text{rad}(n') n' \log q) + \tilde{O}(n \log q)$. We conclude on observing that the above reduction holds for any number field which has complex conjugation as an automorphism, though might not be as efficient for the ring/lattice of interest may have no sparse basis in the canonical embedding.

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