

Recovering Short Generators of Principal Ideals in Cyclotomic Rings

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Abstract

A handful of recent cryptographic proposals rely on the conjectured hardness of the following problem in the ring of integers of a cyclotomic number field: given a basis of a principal ideal that is guaranteed to have a “rather short” generator, find such a generator. Recently, Bernstein and Campbell-Groves-Shepherd sketched potential attacks against this problem; most notably, the latter authors claimed a *polynomial-time quantum* algorithm. (Alternatively, replacing the quantum component with an algorithm of Biasse and Fieker would yield a *classical subexponential-time* algorithm.) A key claim of Campbell *et al.* is that one step of their algorithm—namely, decoding the *log-unit* lattice of the ring to recover a short generator from an arbitrary one—is classically efficient (whereas the standard approach on general lattices takes exponential time). However, very few convincing details were provided to substantiate this claim.

In this work, we clarify the situation by giving a rigorous proof that the log-unit lattice is indeed efficiently decodable, for any cyclotomic of prime-power index. Combining this with the quantum algorithm from a recent work of Biasse and Song confirms the main claim of Campbell *et al.* Our proof consists of two main technical contributions: the first is a geometrical analysis, using tools from analytic number theory, of the standard generators of the group of cyclotomic units. The second shows that for a wide class of typical distributions of the short generator, a standard lattice-decoding algorithm can recover it, given any generator.

By extending our geometrical analysis, as a second main contribution we obtain an efficient algorithm that, given any generator of a principal ideal (in a prime-power cyclotomic), finds a $2^{\tilde{O}(\sqrt{n})}$ -approximate shortest vector in the ideal. Combining this with the result of Biasse and Song yields a quantum polynomial-time algorithm for the $2^{\tilde{O}(\sqrt{n})}$ -approximate Shortest Vector Problem on principal ideal lattices.

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1 Introduction

Over the past several years, *lattices* have emerged as an attractive foundation for cryptography. The most efficient (and potentially practical) lattice-based cryptosystems are related to *ideal lattices*, which correspond to ideals in certain families of rings, e.g., $\mathbb{Z}[X]/(X^{2^k} + 1)$. Representative works include [HPS98, Mic02, LMPR08, Gen09, LPR10].

More recently, a handful of cryptographic constructions have relied directly on *principal* ideals that have “*relatively short*” generators, which serve as secret keys.¹ These include a simplified variant of Gentry’s original fully homomorphic encryption scheme [Gen09] due to Smart and Vercauteren [SV10], the closely related Soliloquy encryption scheme [CGS14], and candidate cryptographic multilinear maps [GGH13, LSS14]. Breaking these systems is no harder than solving the following problem, which we call the *Short Generator of a Principal Ideal Problem* (SG-PIP): given some \mathbb{Z} -basis of an ideal that is guaranteed to have a “short” generator g , find a sufficient short generator (not necessarily g itself).

Potential attacks on SG-PIP in certain rings were sketched by Bernstein [Ber14b] and Campbell, Groves, and Shepherd [CGS14]. The basic structure of the attacks, which appears to be folklore in computational number theory, consists of two main parts:

- First, given a \mathbb{Z} -basis of the principal ideal, find some arbitrary (not necessarily short) generator of the ideal. For this task, which is known as the *Principal Ideal Problem* (PIP), the state of the art is an algorithm of Biase and Fieker [BF14, Bia14], whose running time has only a subexponential $2^{n^{2/3+\epsilon}}$ dependence on n , the degree of the ring (over \mathbb{Z}). In addition, building on the recent work of Eisenträger *et al.* [EHKS14], polynomial-time *quantum* algorithms for PIP have recently been described in two independent works [CGS14, BS15], the latter of which provides a fully rigorous treatment.
- Second, transform the generator found in the previous phase into a *short* generator, thereby recovering the secret key, or its functional equivalent. The standard approach casts this task as a *closest vector problem* (CVP) on the Dirichlet “log-unit” lattice.

In this work, we focus entirely on the second phase, i.e., on recovering a short generator from any generator. At first, one might suspect that this is a hard problem: in general, the fastest known algorithms for CVP (even allowing quantum) run in exponential $2^{\Omega(n)}$ time [MV10, ADS15], or in less time but with much weaker guarantees on the solution quality (e.g., [LLL82, Bab85, Sch87]). In addition, Bernstein [Ber14b] suggested an algebraic approach that may yield slightly subexponential running times in number fields having many subfields, but it remains to be seen if this proposal can be carried through. Regardless of the method used, it is not obvious *a priori* whether solving CVP on the log-unit lattice yields a sufficiently short generator; much depends on the geometry of the lattice (in the relevant norm) and the quality of the solution.

A promising observation made by several researchers [CGS14, Ber14a] is that the CVP instances arising in the second phase have some implicit structure: the existence of a “rather short” generator (by choice of the secret key) implies that the target point is “somewhat close” to the log-unit lattice; CVP with such a distance guarantee is more commonly known as *bounded-distance decoding* (BDD) and is sometimes easier than the general case of CVP. Indeed, Garg, Gentry and Halevi [GGH13] gave an improved variant of the Gentry-Szydlo algorithm [GS02] which shows that in cyclotomic rings having power-of-two index, BDD on the log-unit lattice is efficiently solvable to within sub-polynomial $n^{-\log \log n}$ distance. However, this threshold is much too small to handle the BDD instances arising in cryptosystems.

Campbell, Groves, and Shepherd [CGS14] were the first to claim an efficient solution to the second phase above. In more detail, they asserted that in cyclotomic rings having power-of-two index, the second phase can

¹A principal ideal in a commutative ring R is of the form $gR = \{g \cdot r : r \in R\}$ for some $g \in R$, called a *generator* of the ideal.

be accomplished simply by decoding the log-unit lattice using a standard algorithm such as LLL [LLL82]. However, this claim was not accompanied by a proof.² Nevertheless, experiments in cryptographically relevant choices of dimension have shown that decoding is indeed practically efficient [She14, Sch15], giving strong evidence that the approach of [CGS14] does indeed work.

Contributions. Our first main contribution is a rigorous proof showing that the second phase above can be solved in polynomial time, in any cyclotomic of prime-power index. Our proof is based on classical ideas and results from analytical number theory, along with some techniques from probability theory, and consists of two main technical contributions. First, in Section 3 we use standard tools from analytical number theory, such as bounds on *Dirichlet L-series*, to elucidate the geometry of a standard set of generators for the group of *cyclotomic units*. (The cyclotomic units correspond either to the log-unit lattice itself, or to a sublattice whose index is conjectured to be quite small.) Using this geometry, in Sections 4 and 5 we show that for a wide class of typical distributions of the secret generator—e.g., Gaussian-like distributions—the naïve “round-off” lattice-decoding algorithm [Len82, Bab85] (using the standard generators of the cyclotomic units) can be used to efficiently recover the secret short generator, given any generator of the ideal.³ To complement these results, in Appendix B we give concrete numerical data demonstrating that the second phase succeeds for all practical choices of dimension.

Our second main contribution concerns the questions: in an *arbitrary* principal ideal (of a prime-power cyclotomic), how long can a shortest generator be? And how short of a generator can we find efficiently? In Section 6, we show that for an overwhelming majority of principal ideals, the shortest generator is a $2^{\tilde{O}(\sqrt{n})}$ factor longer than the shortest nonzero vector in the ideal. Moreover, one can efficiently find a generator satisfying this bound, given an arbitrary generator. The first of these facts means that the principal ideals used in the aforementioned cryptographic applications are highly atypical, because their shortest generators are also nearly shortest vectors. The second fact implies that the $2^{\tilde{O}(\sqrt{n})}$ -approximate Shortest Vector Problem (SVP) on arbitrary principal ideals reduces to the Principal Ideal Problem.

Implications and discussion. Combining our main contributions with known algorithms for PIP [BF14, Bia14, CGS14, BS15] (which are the computational bottleneck) yields the following two main implications:

- First, there is a quantum polynomial-time, or classical $2^{n^{2/3+\epsilon}}$ -time, algorithm for SG-PIP, implying a key-recovery attack for the cryptographic constructions of [SV10, GGH13, LSS14, CGS14].
- Second, there is a quantum polynomial-time algorithm for $2^{\tilde{O}(\sqrt{n})}$ -approximate SVP on *principal* ideals in any prime-power cyclotomic. (Note that we do not obtain any improvement over *classical* SVP algorithms, because $2^{n^{2/3}}$ time is sufficient to solve $2^{\tilde{O}(n^{1/3})}$ -approximate SVP on arbitrary lattices [Sch87].)

In light of these, an important open problem is to obtain faster classical PIP algorithms, perhaps also using the guarantee that a short generator exists.

A natural question is what effect, if any, these attacks have on other ring-based problems, such as NTRU [HPS98] and ring-LWE [LPR10], which are the heart of many cryptosystems. Specifically, the

²The explanation given in [CGS14] is that the secret generator corresponds to a vector that is short relative to the determinant of the log-unit lattice. As far as we can tell, this by itself is not enough to substantiate the claim, as it ignores the geometry of the log-unit lattice and the quality of the output produced by the LLL algorithm.

³Strictly speaking, the polynomial running time of this algorithm depends on a number-theoretic conjecture regarding the class numbers $h^+(m)$; see Section 2.4 for details.

theoretical foundation of the ring-LWE problem is the conjectured quantum hardness of approximate-SVP on *arbitrary* ideals, usually in a cyclotomic ring and for (near-)polynomial approximation factors. As far as we can tell, the above-described algorithms do not appear to affect this foundation: the first crucially relies on the existence of an “unusually short” generator, the second is inherently limited to relatively large SVP approximation factors, and both apply only to *principal* ideals. An important question is whether these barriers can be overcome, and if so, whether this leads to attacks on ring-LWE or NTRU themselves.

In a complementary direction, another interesting question is whether the above attacks can be extended to other families of *non-cyclotomic* rings, such as those suggested in [Ber14b]. For this it may suffice to find (by analysis, computation, or both) a suitably good basis of the log-unit lattice, or of a sublattice of not too large index.

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2 Preliminaries

We denote column vectors by lower-case bold letters (e.g., \mathbf{x}) and matrices by upper-case bold letters (e.g., \mathbf{X}). We often adopt the nonstandard, but very useful, convention of indexing rows and columns by particular finite sets (not necessarily $\{1, \dots, n\}$), and identify a matrix with its indexed set of column vectors. The canonical scalar product over \mathbb{R}^n and over \mathbb{C}^n is denoted $\langle \cdot, \cdot \rangle$, and $\|\cdot\|$ denotes the Euclidean norm. For a complex number $z \in \mathbb{C}$, \bar{z} denotes its complex conjugate, and $|z| = \sqrt{z \cdot \bar{z}}$ denotes its magnitude.

2.1 Lattices and BDD

A *lattice* \mathcal{L} is a discrete additive subgroup of \mathbb{R}^n for some positive integer n . The *minimum distance* of \mathcal{L} is $\lambda_1(\mathcal{L}) := \min_{\mathbf{v} \in \mathcal{L} \setminus \{0\}} \|\mathbf{v}\|$, the length of a shortest nonzero lattice vector. Every lattice is generated as the integer linear combinations of some (non-unique) \mathbb{R} -linearly independent *basis* vectors $\mathbf{B} = \{\mathbf{b}_1, \dots, \mathbf{b}_k\}$, as $\mathcal{L} = \mathcal{L}(\mathbf{B}) := \{\sum_{j=1}^k \mathbb{Z} \cdot \mathbf{b}_j\}$, where $k \leq n$ is called the *rank* of the lattice.

Letting span denote the \mathbb{R} -linear span of a set, the *dual basis* $\mathbf{B}^\vee = \{\mathbf{b}_1^\vee, \dots, \mathbf{b}_k^\vee\} \subset \text{span}(\mathbf{B})$ and dual lattice $\mathcal{L} = \mathcal{L}(\mathbf{B}^\vee)$ are defined to satisfy $\langle \mathbf{b}_j^\vee, \mathbf{b}_{j'} \rangle = \delta_{j,j'}$ for all j, j' , where the Kronecker delta $\delta_{j,j'} = 1$ if $j = j'$, and is 0 otherwise. In other words, $\mathbf{B}^t \cdot \mathbf{B}^\vee = (\mathbf{B}^\vee)^t \cdot \mathbf{B}$ is the identity matrix.

In this work we deal with a computational problem on lattices called *bounded-distance decoding* (BDD): given a lattice basis $\mathbf{B} \subset \mathbb{R}^n$ of $\mathcal{L} = \mathcal{L}(\mathbf{B})$ and a target point $\mathbf{t} \in \text{span}(\mathcal{L})$ with the guarantee that $\min_{\mathbf{v} \in \mathcal{L}} \|\mathbf{v} - \mathbf{t}\| \leq r$ for some known $r < \lambda_1(\mathcal{L})/2$, find the unique $\mathbf{v} \in \mathcal{L}$ closest to \mathbf{t} (i.e., such that $\|\mathbf{v} - \mathbf{t}\| \leq r$). In fact, in our context \mathbf{B} and r will be fixed in advance, and \mathbf{t} is the only input that may vary.

A standard approach to solve BDD (and related problems) is the “round-off” algorithm of [Bab85], which simply returns $\mathbf{B} \cdot \lfloor (\mathbf{B}^\vee)^t \cdot \mathbf{t} \rfloor$, where the rounding function $\lfloor c \rfloor := \lfloor c + \frac{1}{2} \rfloor \in \mathbb{Z}$ is applied to each coordinate independently. (Notice that $(\mathbf{B}^\vee)^t \cdot \mathbf{t}$ is the coefficient vector of \mathbf{t} with respect to basis \mathbf{B} .) We recall the following standard fact about this algorithm, and include a brief proof for completeness.

Claim 2.1. *Let $\mathcal{L} \subset \mathbb{R}^n$ be a lattice with basis \mathbf{B} , and let $\mathbf{t} = \mathbf{v} + \mathbf{e} \in \mathbb{R}^n$ for some $\mathbf{v} \in \mathcal{L}$, $\mathbf{e} \in \mathbb{R}^n$. If $\langle \mathbf{b}_j^\vee, \mathbf{e} \rangle \in [-\frac{1}{2}, \frac{1}{2})$ for all j , then on input \mathbf{t} and basis \mathbf{B} , the round-off algorithm outputs \mathbf{v} .*

Proof. Because $\mathbf{v} = \mathbf{B}\mathbf{z}$ for some integer vector \mathbf{z} , we have $(\mathbf{B}^\vee)^t \cdot \mathbf{t} = \mathbf{z} + (\mathbf{B}^\vee)^t \cdot \mathbf{e}$, so by hypothesis on the $\langle \mathbf{b}_j, \mathbf{e} \rangle$, we have $\lfloor (\mathbf{B}^\vee)^t \cdot \mathbf{t} \rfloor = \mathbf{z}$. The claim follows. \square

2.2 Circulant Matrices

We recall some standard facts about *circulant* matrices for a finite abelian group (G, \cdot) , and their relationship with the *characters* of the group. See, e.g., see [Lan02] for further details and proofs.

Definition 2.2 (Circulant matrix). For a vector $\mathbf{a} = (a_g)_{g \in G}$ indexed by G , the G -*circulant* matrix associated with \mathbf{a} is the G -by- G matrix whose (i, j) th entry is $a_{ij^{-1}}$.

Note that the transpose of any G -circulant matrix (associated with $(a_g)_{g \in G}$) is also a G -circulant matrix (associated with $(a_{g^{-1}})_{g \in G}$).

Definition 2.3 (Character group). A *character* is a group morphism $\chi: G \rightarrow \{u \in \mathbb{C} : |u| = 1\}$, i.e., $\chi(g \cdot h) = \chi(g) \cdot \chi(h)$ for all $g, h \in G$. The *character group* (\hat{G}, \cdot) is the set of characters of G , with the group operation being the usual multiplication of functions, i.e., $(\chi \cdot \psi)(g) = \chi(g) \cdot \psi(g)$.

A basic fact is that $|\hat{G}| = |G|$. Notice that for a character $\chi \in \hat{G}$, we have $\overline{\chi(g)} = \chi(g)^{-1} = \chi(g^{-1})$. We identify χ with the vector $(\chi(g))_{g \in G}$. Then all characters χ have Euclidean norm $\|\chi\| = \sqrt{|G|}$, because

$$\langle \chi, \chi \rangle = \sum_{g \in G} \chi(g) \cdot \overline{\chi(g)} = \sum_{g \in G} 1 = |G|.$$

Moreover, distinct characters χ, ψ are orthogonal:

$$\langle \chi, \psi \rangle = \sum_{g \in G} \chi(g) \cdot \overline{\psi(g)} = \sum_{g \in G} (\chi \cdot \psi^{-1})(g) = 0.$$

Therefore, the complex G -by- \hat{G} matrix

$$\mathbf{P}_G := |G|^{-1/2} \cdot (\chi(g))_{g \in G, \chi \in \hat{G}}$$

is unitary, i.e., $\mathbf{P}_G^{-1} = \mathbf{P}_G^*$, the conjugate transpose of \mathbf{P}_G .

Lemma 2.4. A complex matrix \mathbf{A} is G -circulant if and only if the \hat{G} -by- \hat{G} matrix $\mathbf{P}_G^{-1} \cdot \mathbf{A} \cdot \mathbf{P}_G$ is diagonal; equivalently, the columns of \mathbf{P}_G are the eigenvectors of \mathbf{A} . If \mathbf{A} is the G -circulant matrix associated with $\mathbf{a} = (a_g)_{g \in G}$, its eigenvalue corresponding to $\chi \in \hat{G}$ is $\lambda_\chi = \langle \mathbf{a}, \chi \rangle = \sum_{g \in G} a_g \cdot \overline{\chi(g)}$.

It follows that every row and column of \mathbf{A} has squared Euclidean norm

$$\|\mathbf{a}\|^2 = \|\mathbf{P}_G^* \cdot \mathbf{a}\|^2 = |G|^{-1} \cdot \sum_{\chi \in \hat{G}} |\lambda_\chi|^2.$$

It also follows that \mathbf{A}^{-1} (when defined) is G -circulant, with eigenvalue λ_χ^{-1} for eigenvector χ .

Proof. Suppose that \mathbf{A} is G -circulant, and let $\chi \in \hat{G}$ be a character of G . Then

$$(\mathbf{A} \cdot \chi)_g = \sum_{h \in G} a_{gh^{-1}} \cdot \chi(h) = \left(\sum_{k \in G} a_k \cdot \overline{\chi(k)} \right) \cdot \chi(g),$$

where in the final equality we have substituted $k = gh^{-1}$ and used $\chi(h) = \overline{\chi(k)} \cdot \chi(g)$. So $\mathbf{A} \cdot \chi = \lambda_\chi \cdot \chi$.

For the other direction, it suffices by linearity to show that $\mathbf{A}_\chi = \mathbf{P}_G \cdot \mathbf{D}_\chi \cdot \mathbf{P}_G^{-1}$ is G -circulant for every $\chi \in \hat{G}$, where \mathbf{D}_χ is the diagonal \hat{G} -by- \hat{G} matrix with 1 in its (χ, χ) th entry and zeros elsewhere. Indeed, by definition of \mathbf{P}_G and because $\mathbf{P}_G^{-1} = \mathbf{P}_G^*$, the (i, j) th entry of \mathbf{A}_χ is simply $|G|^{-1} \cdot \chi(i) \cdot \overline{\chi(j)} = |G|^{-1} \cdot \chi(ij^{-1})$, which depends only on ij^{-1} as required. \square

2.3 Dirichlet Characters and L -Series

A *Dirichlet character* χ is a character of \mathbb{Z}_k^* for some positive integer k . Note that if $k|\ell$ then χ induces a character of \mathbb{Z}_ℓ^* via the natural morphism $\mathbb{Z}_\ell^* \rightarrow \mathbb{Z}_k^*$, so we can equivalently view χ as being defined modulo either k or ℓ . The *conductor* f_χ of χ is the smallest positive f such that χ is induced by a Dirichlet character modulo f . The character is said to be *even* if $\chi(-1) = 1$; note that the even Dirichlet characters correspond with the characters of $\mathbb{Z}_k^*/\{\pm 1\}$. The character is said to be *quadratic* if all its values are real (i.e., ± 1), and it is not the constant 1 character (which is known as the principal character). We often implicitly extend χ to a completely multiplicative function from \mathbb{Z} to \mathbb{C} , by letting $\chi(a) = 0$ if $\gcd(a, k) > 1$.

Definition 2.5 (Dirichlet L -Series). For a Dirichlet character χ , the Dirichlet L -function $L(\cdot, \chi)$ is defined as the formal series

$$L(s, \chi) = \sum_{k \geq 1} \frac{\chi(k)}{k^s}.$$

For any Dirichlet character χ , the series $L(s, \chi)$ is absolutely convergent for all $s \in \mathbb{C}$ with $\Re(s) > 1$. It is also known that $L(1, \chi)$ converges and is nonzero for any non-principal Dirichlet character (i.e., $\chi \neq 1$). We have the following asymptotic bounds on its value; we will only use the lower bounds.

Theorem 2.6. *There exists a $C > 0$ such that, for any non-quadratic character χ of conductor $f > 1$,*

$$\frac{1}{\ell(f)} \leq |L(1, \chi)| \leq \ell(f) \quad \text{where } \ell(f) = C \ln f. \quad (1)$$

Moreover, for any quadratic character χ ,

$$|L(1, \chi)| \geq \frac{1}{C\sqrt{f}}. \quad (2)$$

Equation (1) can be traced back to Landau [Lan27], and improving the constant C is an active field of research [Lou15]. Equation (2) is also classical and follows from Dirichlet's class number formula (see, e.g., [MV06, Section 4.4]). We note that under the Generalized Riemann Hypothesis, the bound in Eq. (1) can be improved to $\ell(f) = C \ln \ln f$, and holds for both quadratic and non-quadratic characters (see, e.g., [LLS15]).

2.4 Cyclotomic Number Fields and the Log-Unit Lattice

Cyclotomic number fields. Let L be a field. An element $\zeta \in L$ is a root of unity if $\zeta^m = 1$ for some positive integer m . The order of a root of unity $\zeta \in L$ is the order of the finite multiplicative subgroup of L^* generated by ζ . A primitive m th root of unity in L is a root of unity $\zeta \in L$ of order m . Note that if $\zeta \in L$ is a primitive m th root of unity, then the polynomial $X^m - 1 \in L[X]$ factors as $\prod_{i=0}^{m-1} (X - \zeta^i)$ over $L[X]$. Also note that the complete set of primitive m th roots in L consists of the powers ζ^j for $j \in \mathbb{Z}_m^*$.

An algebraic number field K is an extension field of the rationals \mathbb{Q} such that its dimension $[K : \mathbb{Q}]$ as a \mathbb{Q} -vector space (i.e., its degree) is finite. If $\Omega \supset K$ is an extension field such that Ω is algebraically closed over \mathbb{Q} , then there are exactly $[K : \mathbb{Q}]$ field embeddings of K into Ω .⁴ An algebraic number field is Galois if the order of its automorphism group equals its degree.⁵ A number field K is cyclotomic if $K = \mathbb{Q}(\zeta)$ for some root of unity $\zeta \in K$. Its degree is $\varphi(m)$, where $\varphi(\cdot)$ is the Euler totient function and m is the order of ζ , and its ring of integers R is monogenic, i.e., $R = \mathbb{Z}[\zeta]$. We let U denote the cyclic (multiplicative) subgroup of m th roots of unity, which is generated by ζ .

A cyclotomic number field is Galois. If $K = \mathbb{Q}(\zeta)$ is a cyclotomic number field with $\zeta \in K$ an m th primitive root of unity then each automorphism is characterized by the assignment $\zeta \mapsto \zeta^j$ for some $j \in \mathbb{Z}_m^*$. As a consequence, if L is an extension field of a cyclotomic field K , then K is situated uniquely in L . For concreteness, we situate cyclotomic number fields in the complex numbers \mathbb{C} . Let m be a positive integer and define $\omega = \omega_m = \exp(2\pi i/m) \in \mathbb{C}$. Then ω is a primitive m th root of unity and $K = \mathbb{Q}(\omega)$ is the m th cyclotomic number field. The embeddings of K into the complex numbers (i.e., the automorphisms of K) are denoted σ_j for $j \in \mathbb{Z}_m^*$, where σ_j sends ω to ω^j .

Logarithmic embedding. The embeddings σ_i of K , being complex, come in conjugate pairs, i.e., $\sigma_j(x) = \overline{\sigma_{-j}(x)}$. We will mainly be concerned with their *magnitudes*, so we identify the pairs by indexing over the multiplicative quotient group $G := \mathbb{Z}_m^*/\{\pm 1\}$. We then have the *logarithmic embedding*, defined as

$$\begin{aligned} \text{Log}: K &\rightarrow \mathbb{R}^{\varphi(m)/2} \\ a &\mapsto (\log|\sigma_i(a)|)_{i \in G}. \end{aligned}$$

The logarithmic embedding defines a group morphism, mapping the multiplicative group K^* to an additive subgroup of $\mathbb{R}^{\varphi(m)/2}$. The kernel of Log restricted to R^* is $\{\pm 1\} \cdot U$. The Dirichlet Unit Theorem (see [Sam70, Chapter 4.4, Theorem 1]) implies that $\Lambda = \text{Log}(R^*)$, the image of the multiplicative unit group of R under the logarithmic embedding, is a full-rank lattice in the linear subspace of $\mathbb{R}^{\varphi(m)/2}$ orthogonal to the all-1s vector $\mathbf{1}$. We refer to Λ as the *log-unit lattice*.

Cyclotomic units. Let A be the multiplicative subgroup of K^* generated by $\pm\zeta$ and

$$z_j := \zeta^j - 1, \quad j \in \mathbb{Z}_m \setminus \{0\}.$$

Notice that $z_j = -\zeta^j \cdot z_{-j}$, so z_j and z_{-j} are equivalent modulo $\pm U$; in particular, $\text{Log}(z_j) = \text{Log}(z_{-j})$. The group of *cyclotomic units*, denoted C , is defined by

$$C = A \cap R^*.$$

The z_j given above are not necessarily units in R , and thus do not generate C . However, a closely related generating set, which we call the *canonical generators*, is given by the following lemma. Recall that $G = \mathbb{Z}_m^*/\{\pm 1\}$, and identify it with some canonical set of representatives in \mathbb{Z}_m^* .

Lemma 2.7 (Lemma 8.1 of [Was97]). *Let m be a prime power, and define $b_j := z_j/z_1 = (\zeta^j - 1)/(\zeta - 1)$. The group C of cyclotomic units is generated by $\pm\zeta$ and b_j for $j \in G \setminus \{1\}$.*

⁴These embeddings are merely ring morphisms $\psi : K \rightarrow \Omega$. Each such ψ is automatically injective because K is a field. Also note that any such ψ fixes \mathbb{Q} pointwise.

⁵An automorphism of a field L is a ring isomorphism $\psi : L \rightarrow L$. The automorphisms of L form a group with functional composition as the group operation.

Notice that $\text{Log } C$ is a sublattice of Λ . As shown below, the index of Λ over $\text{Log } C$ is finite. In fact, it is $h^+(m)$, the *class number* of the real subfield $K^+ = \mathbb{Q}(\zeta + \bar{\zeta})$, defined as the index of the subgroup of principal fractional ideals in the multiplicative group of all fractional ideals (in K^+). The proof of this theorem is left as Exercise 8.5 in [Was97]. For completeness, we sketch the solution in Appendix A.

Theorem 2.8. *For a prime power $m > 2$, the index of the log-unit lattice Λ over $\text{Log } C$ is*

$$[\Lambda : \text{Log } C] = h^+(m).$$

Some facts and conjectures concerning h^+ . For our purposes, we need $h^+(m)$ not to be very big. For all power-of-two m up to $m = 256$, and also for $m = 512$ under GRH, it is known that $h^+(m) = 1$ (see [Mil14]). Whether $h^+(m) = 1$ for all power-of-two m is known as Weber's class number problem, and is presented in the literature as a reasonable conjecture.

In the case of odd primes, it also appears that h^+ is quite small. Computations of Schoof [Sch03] and Miller [Mil15] show that $h^+(p) \leq 11$ for all primes $p \leq 241$. For powers of odd primes it has been conjectured (with support of the Cohen-Lenstra heuristic) that, for all but finitely many pairs (p, ℓ) where p is a prime, $h^+(p^{\ell+1}) = h^+(p^\ell)$ [BPR04]. A direct consequence is that $h^+(p^\ell)$ is bounded for a fixed p and increasing ℓ .

3 Geometry of the Canonical Generators

Throughout this section, let the cyclotomic index m be a prime power. Our goal here is to show that the canonical generators of the cyclotomic units, under the logarithmic embedding, are geometrically well-suited for bounded-distance decoding.

Recalling that $G = \mathbb{Z}_m^*/\{\pm 1\}$ is identified with some set of canonical representatives in \mathbb{Z}_m^* and that $\text{Log}(b_j) = \text{Log}(b_{-j})$, define

$$\mathbf{b}_j = \text{Log}(b_j), \quad j \in G \setminus \{1\},$$

to be the log-embeddings of the canonical generators $b_j = (\zeta^j - 1)/(\zeta - 1)$ defined in Lemma 2.7. By Lemma 2.7, these \mathbf{b}_j form a basis of the sublattice $\text{Log } C$, which by Theorem 2.8 has index $h^+(m)$ in Λ .

In order to apply the round-off algorithm and Claim 2.1 with this basis, we bound the norms $\|\mathbf{b}_j^\vee\|$ of the dual basis vectors. The remainder of this section is dedicated to proving the following theorem.

Theorem 3.1. *Let $m = p^k$ for a prime p , and let $\{\mathbf{b}_j^\vee\}_{j \in G \setminus \{1\}}$ denote the basis dual to $\{\mathbf{b}_j\}_{j \in G \setminus \{1\}}$. Then all $\|\mathbf{b}_j^\vee\|$ are equal, and*

$$\|\mathbf{b}_j^\vee\|^2 \leq 2k|G|^{-1} \cdot (\ell(m)^2 + O(1)) = O(m^{-1} \cdot \log^3 m).$$

To prove the theorem we start by relating the basis vectors \mathbf{b}_j to a certain G -circulant matrix. Recalling that $z_j = \zeta^j - 1$ is the numerator of b_j , define

$$\mathbf{z}_j := \text{Log}(z_j) = \mathbf{b}_j + \mathbf{z}_1. \quad (3)$$

Collect these vectors into a square G -by- G matrix \mathbf{Z} whose j th column is \mathbf{z}_{j-1} , and notice that its (i, j) th entry $\log|\omega^{i \cdot j^{-1}} - 1|$ is determined by $i j^{-1} \in G$ alone, so \mathbf{Z} is the G -circulant matrix associated with \mathbf{z}_1 . For each eigenvector $\chi \in \hat{G}$ of \mathbf{Z} , let $\lambda_\chi := \langle \mathbf{z}_1, \chi \rangle$ denote the corresponding eigenvalue.

Lemma 3.2. *For all $j \in G \setminus \{1\}$ we have*

$$\|\mathbf{b}_j^\vee\|^2 = |G|^{-1} \cdot \sum_{\chi \in \hat{G} \setminus \{1\}} |\lambda_\chi|^{-2}. \quad (4)$$

Proof. Let \mathbf{z}_j^\vee denote the vectors dual to the \mathbf{z}_j , i.e., the columns of \mathbf{Z}^{-t} . (As shown below in the proof of Theorem 3.1, \mathbf{Z}^{-1} is indeed well defined because all eigenvalues λ_χ of \mathbf{Z} are nonzero.)

We first claim that \mathbf{b}_j^\vee is simply the projection of \mathbf{z}_j^\vee orthogonal to $\mathbf{1}$, i.e., $\mathbf{b}_j^\vee = \mathbf{z}_j^\vee - |G|^{-1} \cdot \langle \mathbf{z}_j^\vee, \mathbf{1} \rangle \cdot \mathbf{1}$. Indeed, these vectors are all in $\text{span}(\mathbf{b}_{j'}^\vee)_{j'}$, the space orthogonal to $\mathbf{1}$, and moreover, for all $j, j' \in G \setminus \{1\}$ they satisfy

$$\langle \mathbf{z}_j^\vee - |G|^{-1} \cdot \langle \mathbf{z}_j^\vee, \mathbf{1} \rangle \cdot \mathbf{1}, \mathbf{b}_{j'}^\vee \rangle = \langle \mathbf{z}_j^\vee, \mathbf{b}_{j'}^\vee \rangle = \langle \mathbf{z}_j^\vee, \mathbf{z}_{j'}^\vee - \mathbf{z}_1^\vee \rangle = \delta_{j,j'} - 0.$$

Now,

$$\|\mathbf{b}_j^\vee\|^2 = \|\mathbf{z}_j^\vee\|^2 - |G|^{-1} \cdot \langle \mathbf{z}_j^\vee, \mathbf{1} \rangle^2.$$

Recall by Lemma 2.4 that \mathbf{Z}^{-t} is the G -circulant matrix associated with \mathbf{z}_1^\vee , which has eigenvalue $\lambda_\chi^{-1} = \langle \mathbf{z}_1^\vee, \chi \rangle$ for eigenvector $\chi \in \hat{G}$. By the remarks following Lemma 2.4, $\|\mathbf{z}_j^\vee\|^2 = |G|^{-1} \cdot \sum_{\chi \in \hat{G}} |\lambda_\chi|^{-2}$. The lemma follows by noting that $\langle \mathbf{z}_j^\vee, \mathbf{1} \rangle = \langle \mathbf{z}_1^\vee, \mathbf{1} \rangle = \lambda_1^{-1}$. \square

We now provide an upper bound on the right-hand side of Equation (4). Our proof is similar to the proof that the cyclotomic units have finite index in the full group of units [Was97, Theorem 8.2].

Theorem 3.3 ([Was97, Lemma 4.8 and Theorem 4.9]). *Let χ be an even Dirichlet character of conductor $f > 1$, and let $\omega_f = \exp(2\pi i/f) \in \mathbb{C}$. Then*

$$\left| \sum_{a \in \mathbb{Z}_f^*} \overline{\chi(a)} \cdot \log|1 - \omega_f^a| \right| = \sqrt{f} \cdot |L(1, \chi)|.$$

For completeness, we briefly explain how the finite sum on the left hand side gives rise to an L -series, and refer to [Was97] for the details. Using the Taylor expansion

$$\log|1 - x| = - \sum_{k \geq 1} x^k / k,$$

one gets a sum over finitely many a and infinitely many k of terms $\overline{\chi(a)} \cdot \omega_f^{ak} / k$. For a fixed k , the sum over a can easily be rewritten as $\tau(\chi) \cdot \chi(k) / k$, where $\tau(\chi)$ is a Gauss sum (see [Was97, Lemma 4.7]), which makes the Dirichlet L -function apparent.

Corollary 3.4. *Suppose $f > 1$ divides a prime power m . For any even Dirichlet character χ of conductor f ,*

$$\left| \sum_{a \in \mathbb{Z}_m^*} \overline{\chi(a)} \cdot \log|1 - \omega_m^a| \right| = \sqrt{f} \cdot |L(1, \chi)|.$$

Proof. Let $\phi: \mathbb{Z}_m^* \rightarrow \mathbb{Z}_f^*$ be the map given by reduction modulo f . We have

$$\begin{aligned} \sum_{a \in \mathbb{Z}_m^*} \overline{\chi(a)} \cdot \log|1 - \omega_m^a| &= \sum_{a \in \mathbb{Z}_f^*} \overline{\chi(a)} \sum_{\substack{b \in \mathbb{Z}_m^* \\ \phi(b)=a}} \log|1 - \omega_m^b| \\ &= \sum_{a \in \mathbb{Z}_f^*} \overline{\chi(a)} \cdot \log \left| \prod_{\substack{b \in \mathbb{Z}_m^* \\ \phi(b)=a}} (1 - \omega_m^b) \right| \\ &= \sum_{a \in \mathbb{Z}_f^*} \overline{\chi(a)} \cdot \log|1 - \omega_f^a|, \end{aligned}$$

where in the last equality we have used the identity $\prod_{i \in \mathbb{Z}_n} (1 - \omega_n^i Y) = 1 - Y^n$ and $\omega_m^n = \omega_f$ with $n = m/f$. The claim follows by applying Theorem 3.3. \square

We are now ready to complete the proof of the main theorem.

Proof of Theorem 3.1. Recall that the characters $\chi \in \hat{G}$ correspond to the even characters of \mathbb{Z}_m^* , because $\chi(\pm 1) = 1$. Also recall that by Lemma 2.4, the eigenvalues are

$$\lambda_\chi = \langle \mathbf{z}_1, \chi \rangle = \sum_{a \in G} \overline{\chi(a)} \cdot \log|1 - \omega_m^a| = \frac{1}{2} \sum_{a \in \mathbb{Z}_m^*} \overline{\chi(\pm a)} \cdot \log|1 - \omega_m^a|,$$

where the second equality holds because $|1 - \omega_m^{-a}| = |1 - \omega_m^a|$. Therefore, using Corollary 3.4 we have

$$|\lambda_\chi| = \frac{1}{2} \sqrt{f_\chi} \cdot |L(1, \chi)|, \quad (5)$$

and so by Lemma 3.2,

$$\|\mathbf{b}_j^\vee\|^2 = |G|^{-1} \cdot \sum_{\chi \in \hat{G} \setminus \{1\}} |\lambda_\chi|^{-2} = 4|G|^{-1} \cdot \sum_{\chi \in \hat{G} \setminus \{1\}} f_\chi^{-1} \cdot |L(1, \chi)|^{-2}.$$

We first consider the contribution to the sum coming from quadratic characters. When p is an odd prime, there is exactly one quadratic character (see [MV06, Section 9.3]), and it is of conductor p , hence by Equation (2) in Theorem 2.6, the contribution to the sum is $O(1)$. In the case $p = 2$ the contribution is also $O(1)$ since there are at most three quadratic characters (see again [MV06, Section 9.3]) of constant conductor. Finally, the contribution coming from non-quadratic characters is at most

$$\ell(m)^2 \sum_{\chi \in \hat{G} \setminus \{1\}} f_\chi^{-1} \leq \frac{k}{2} \cdot \ell(m)^2,$$

where we used Equation (1) in Theorem 2.6 and Claim 3.5 below. \square

Claim 3.5. *Let $m = p^k$ for a prime p . Then, for $G = \mathbb{Z}_m^* / \{\pm 1\}$,*

$$\sum_{\chi \in \hat{G} \setminus \{1\}} f_\chi^{-1} \leq \frac{k}{2}.$$

Proof. Notice that there are at most f Dirichlet characters of conductor f , at most half of which are even (when $f > 1$), so

$$\sum_{\chi \in \hat{G} \setminus \{1\}} f_\chi^{-1} \leq \sum_{\ell=1}^k \frac{p^\ell}{2} \cdot \frac{1}{p^\ell} = \frac{k}{2}. \quad \square$$

4 Algorithmic Implications

The following is our main algorithmic result, showing that under mild restrictions on the distribution of the short generator, we can recover it from any generator that differs from it by a unit in C . Roughly speaking, the requirement from the distribution is that the *ratios* between its complex embeddings are not too large. We note that since the \mathbf{v}_i below are assumed to be orthogonal to the all-1 vector, the *scale* of the distribution (or variance in the case of Gaussians) is irrelevant: this should not come as a surprise, since, e.g., one can normalize the input generator g' to have algebraic norm 1.

Theorem 4.1. *Let D be a distribution over $\mathbb{Q}(\zeta)$ with the property that for any tuple of vectors $\mathbf{v}_1, \dots, \mathbf{v}_{\varphi(m)/2-1} \in \mathbb{R}^{\varphi(m)/2}$ of Euclidean norm 1 that are orthogonal to the all-1 vector $\mathbf{1}$, the probability that $|\langle \text{Log}(g), \mathbf{v}_i \rangle| < c\sqrt{m} \cdot (\log m)^{-3/2}$ holds for all i is at least some $\alpha > 0$, where g is chosen from D and c is a universal constant. Then there is an efficient algorithm that given $g' = g \cdot u$, where g is chosen from D and $u \in C$ is a cyclotomic unit, outputs an element of the form $\pm \zeta^j g$ with probability at least α .*

Proof. The algorithm applies the round-off algorithm from Claim 2.1 to $\text{Log}(g') = \text{Log}(g) + \text{Log}(u)$, using the vectors \mathbf{b}_j (defined and analyzed in Section 3) as the basis. By the assumption on D and Theorem 3.1, with probability at least α the output is $\text{Log}(u) \in \text{Log}(C)$. We next find integer coefficients a_j such that $\text{Log}(u) = \sum a_j \mathbf{b}_j$, and compute $u' = \prod b_j^{a_j}$. Since $\text{Log}(u') = \text{Log}(u)$ it follows that u' must be of the form $\pm \zeta^j u$ for some sign and some j . Therefore, g'/u' is the desired element. \square

In the next section we show that the condition on D in the theorem is satisfied by several natural distributions.

One possible concern with the above algorithm is that it expects as input $g \cdot u$ for a *cyclotomic unit* $u \in C$, whereas the first phase of the attack described in the introduction, i.e., a PIP algorithm, is only guaranteed to output $g \cdot u$ for an *arbitrary unit* $u \in R^*$. There are several reasons why this should not be an issue. First, as mentioned in Section 2, in some cases, e.g., for power-of-2 cyclotomic, it is conjectured that $C = R^*$. More generally, the index of C in R^* , which we recall is h^+ , the class number of the totally real subfield, is often small. In such a case, if we have a list of coset representatives of C in R^* , we can enumerate over all of them and use the algorithm above to recover g , increasing the running time only by a factor of h^+ . In order to obtain such a list of representatives, we can use an algorithm for computing the unit group, either classical [BF14] or quantum [EHKS14]. These algorithms are no slower than the known PIP algorithms and moreover, need only be applied once for a given cyclotomic field (as opposed to once for each public key). Alternatively, by running the PIP algorithm multiple times on a basis of a principal ideal with a *known* short generator chosen using the secret key generation algorithm, we can recover a list of representatives for all the cosets that show up as output of the PIP algorithm with non-negligible probability; we can then enumerate over that list.

In the above statement and proof we glossed over issues of precision and assumed for simplicity, as one often does, that the input g' is given exactly. To be fully rigorous, one needs to verify that the algorithm can deal with inputs that are specified with finite precision, and still runs in time polynomial in its input size. Typically, by finite precision one means that the input is given in fixed-point representation, providing additive approximation to the true numbers. Here, however, it is more natural to assume that the input is given in (the strictly more general) floating-point representation, providing multiplicative approximation to the true numbers. Not only is this more natural, but also the known PIP algorithms [BF14, Bia14, BS15] generate an output in this format, or an output that can be easily converted to this format.⁶ Luckily, dealing with floating-

⁶In general number fields (in fact already in quadratic number fields), the use of floating point is *necessary*, since generators are typically doubly exponentially large and so would require exponential time to write down in fixed-point notation.

point inputs is straightforward. First notice that $\text{Log}(g')$ can be written in standard fixed-point representation, and so can $\text{Log}(u)$. The integer coefficients a_j can be stored exactly since they are at most exponential in the input size. Finally, by using a sufficiently good multiplicative approximation of b_j (with the multiplicative error being much less than $1/a_j$), we can obtain an arbitrarily good multiplicative approximation of u' . As a result we get a multiplicative approximation of the desired output g'/u' that can be made essentially as good as the multiplicative approximation of the input g' .

5 Tail Bounds

In this section we show that the condition on D in Theorem 4.1 is satisfied by two natural distributions: the continuous Gaussian and a wide enough discrete Gaussian (over any lattice). This section is independent of the other sections in this paper, and we avoid the use of notation from algebraic number theory. Instead, we identify elements of K with vectors in $\mathbb{R}^{\varphi(m)}$ by taking the real and the imaginary part of their $\varphi(m)/2$ complex embeddings, i.e., a is mapped to $(\Re(\sigma_j(a)), \Im(\sigma_j(a)))_{j \in G}$. As a result, all random variables appearing here are real. The results in this section should be easy to extend to other distributions.

We start with Lemma 5.2, a tail bound on the sum of subexponential random variables. The proof is based on a standard Bernstein argument, and follows the proof in [Ver12] apart from some minor modifications for convenience.

Definition 5.1. For $\alpha, \beta > 0$, a random variable X is (α, β) -subexponential if

$$\mathbb{E}[\cosh(\alpha X)] \leq \beta,$$

where recall that $\cosh(x) := (e^x + e^{-x})/2$.

Lemma 5.2 (Tail bound). Let X_1, \dots, X_n be independent centered (i.e., expectation zero) (α, β) -subexponential random variables. Then, for any $\mathbf{a} = (a_1, \dots, a_n) \in \mathbb{R}^n$ and every $t \geq 0$,

$$\Pr\left[\left|\sum a_i X_i\right| \geq t\right] \leq 2 \exp\left(-\min\left(\frac{\alpha^2 t^2}{8\beta \|\mathbf{a}\|_2^2}, \frac{\alpha t}{2\|\mathbf{a}\|_\infty}\right)\right).$$

Proof. By scaling, we can assume without loss of generality that $\alpha = 1$. Next, we use the inequality

$$e^{\delta x} - \delta x - 1 \leq (e^{\delta x} - \delta x - 1) + (e^{-\delta x} + \delta x - 1) = 2(\cosh(\delta x) - 1) \leq 2\delta^2(\cosh(x) - 1)$$

which holds for all $-1 \leq \delta \leq 1$ and all $x \in \mathbb{R}$, where the second inequality follows from the Taylor expansion. By applying this inequality to a $(1, \beta)$ -subexponential centered random variable X , and taking expectations we see that for all $-1 \leq \delta \leq 1$,

$$\begin{aligned} \mathbb{E}[\exp(\delta X)] &\leq 1 + 2\delta^2 \mathbb{E}[\cosh(X) - 1] \\ &\leq 1 + 2\delta^2(\beta - 1) \leq \exp(2\delta^2\beta). \end{aligned} \tag{6}$$

Using Markov's inequality, we can bound the upper tail probability for any $\lambda > 0$ as

$$\begin{aligned} \Pr\left[\sum a_i X_i \geq t\right] &= \Pr\left[\exp\left(\lambda \sum a_i X_i\right) \geq \exp(\lambda t)\right] \\ &\leq \exp(-\lambda t) \cdot \mathbb{E}\left[\exp\left(\lambda \sum a_i X_i\right)\right] \\ &= \exp(-\lambda t) \cdot \prod \mathbb{E}[\exp(\lambda a_i X_i)] \\ &\leq \exp(-\lambda t + 2\beta \lambda^2 \|\mathbf{a}\|_2^2), \end{aligned}$$

where in the second inequality we used (6) and assumed that $\lambda \|\mathbf{a}\|_\infty \leq 1$. Taking $\lambda = \min(t/(4\beta\|\mathbf{a}\|_2^2), 1/\|\mathbf{a}\|_\infty)$ this bound becomes at most

$$\exp\left(-\min\left(\frac{t^2}{8\beta\|\mathbf{a}\|_2^2}, \frac{t}{2\|\mathbf{a}\|_\infty}\right)\right).$$

We complete the proof by applying the same argument with $-\mathbf{a}$. \square

The next claim follows immediately from Definition 5.1.

Claim 5.3. *If Y is a non-negative random variable such that both $\mathbb{E}[Y]$ and $\mathbb{E}[Y^{-1}]$ are finite, then $\log Y$ is a $(1, \beta)$ -subexponential random variable for some $\beta > 0$.*

The following is an immediate corollary of the tail bound. It shows that the condition in Theorem 4.1 holds with overwhelming probability for a continuous Gaussian distribution of any radius that is spherical in the embedding basis. Notice that the parameter r plays no role in the conclusion of the statement.

Lemma 5.4. *Let $X_1, \dots, X_n, X'_1, \dots, X'_n$ be i.i.d. $N(0, r)$ variables for some $r > 0$, and let $\hat{X}_i = (X_i^2 + X_i'^2)^{1/2}$. Then, for any vectors $\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(\ell)} \in \mathbb{R}^n$ of Euclidean norm 1 that are orthogonal to the all-1 vector, and every $t \geq C$ for some universal constant C ,*

$$\Pr\left[\exists j, \left|\sum_i a_i^{(j)} \log(\hat{X}_i)\right| \geq t\right] \leq 2\ell \exp(-t/2).$$

Proof. By union bound, it suffices to prove the lemma for the case $\ell = 1$, and we let $\mathbf{a} = \mathbf{a}^{(1)}$. Since $\sum a_i = 0$, we can assume without loss of generality that $r = 1$. Notice that \hat{X}_i has a chi distribution with 2 degrees of freedom (also known as a Rayleigh distribution) whose density function is given by $xe^{-x^2/2}$ for $x > 0$ and zero otherwise. In particular, it is easy to see that both $\mathbb{E}[\hat{X}_i]$ and $\mathbb{E}[\hat{X}_i^{-1}]$ are finite (both are $\sqrt{\pi/2}$). Therefore, by Claim 5.3, $\log \hat{X}_i$ is $(1, \beta)$ subexponential for some constant $\beta > 0$. From this it follows that $\hat{X}_i = \log \hat{X}_i - \mathbb{E}[\log \hat{X}_i]$ are centered $(1, \beta')$ subexponential random variables for some constant $\beta' > 0$. The result now follows by applying Lemma 5.2 to $\hat{X}_1, \dots, \hat{X}_n$, using the bound $\|\mathbf{a}\|_\infty \leq 1$, and the observation that $\sum_i a_i \mathbb{E}[\log \hat{X}_i] = 0$. \square

In the next lemma we show that small perturbations of the continuous Gaussian distribution still satisfy the condition in Theorem 4.1.

Lemma 5.5. *Let $X = (X_1, \dots, X_n, X'_1, \dots, X'_n)$ be i.i.d. $N(0, r)$ variables for some $r > 0$, and let $Y = (Y_1, \dots, Y_n, Y'_1, \dots, Y'_n)$ be a (not necessarily independent) random vector satisfying $\|Y\|_2 \leq u$ with probability 1 for some $u \leq r/(20\sqrt{n})$. Let $Z = X + Y$ and define $\hat{X}_i, \hat{Y}_i, \hat{Z}_i$ as before. Then for any vectors $\mathbf{a}^{(1)}, \dots, \mathbf{a}^{(\ell)} \in \mathbb{R}^n$ of Euclidean norm 1 that are orthogonal to the all-1 vector, it holds with constant probability that for all j ,*

$$\left|\sum_i a_i^{(j)} \log(\hat{Z}_i)\right| \leq 1 + 10 \log \ell.$$

Proof. By Lemma 5.4 we have that with some constant probability close to 1,

$$\forall j, \left|\sum_i a_i^{(j)} \log(\hat{X}_i)\right| < 10 \log \ell. \quad (7)$$

Moreover, since $\hat{X}_i < r/(10\sqrt{n})$ implies that both $|X_i|$ and $|X'_i|$ are smaller than $r/(10\sqrt{n})$, we see that by independence of X_i, X'_i , the probability of the former event is at most c/n for some small constant c . As a result we have that with constant probability close to 1,

$$\forall i, \hat{X}_i > r/(10\sqrt{n}).$$

In the following we assume that these two conditions hold (which happens with constant probability close to 1 by union bound), and bound the effect of Y . Now let \mathbf{a} be one of the vectors in the statement of the lemma. Then,

$$\begin{aligned} \left| \sum_i a_i \log(\hat{Z}_i) \right| &\leq \left| \sum_i a_i \log(\hat{X}_i) \right| + \left| \sum_i a_i \log(\hat{Z}_i/\hat{X}_i) \right| \\ &\leq 10 \log \ell + \left| \sum_i a_i \log(\hat{Z}_i/\hat{X}_i) \right|, \end{aligned}$$

where we used Eq. (7). Notice that by the triangle inequality (for two-dimensional Euclidean space),

$$\hat{X}_i - \hat{Y}_i \leq \hat{Z}_i \leq \hat{X}_i + \hat{Y}_i.$$

Since $\hat{Y}_i \leq \|Y\|_2 \leq u \leq r/(20\sqrt{n}) \leq \hat{X}_i/2$, and using the inequality $|\log(1 + \delta)| \leq 2|\delta|$ valid for all $\delta \in [-1/2, 1/2]$,

$$\begin{aligned} \left| \sum_i a_i \log(\hat{Z}_i/\hat{X}_i) \right| &\leq \left(\sum_i (\log(\hat{Z}_i/\hat{X}_i))^2 \right)^{1/2} \\ &\leq \left(\sum_i (2\hat{Y}_i/\hat{X}_i)^2 \right)^{1/2} \\ &\leq 20\sqrt{n}/r \cdot \left(\sum_i \hat{Y}_i^2 \right)^{1/2} \\ &\leq 20\sqrt{nu}/r \leq 1, \end{aligned}$$

where the first inequality follows from Cauchy-Schwarz. \square

Finally, we consider the spherical (in the embedding basis) discrete Gaussian distribution over an arbitrary lattice $L \subseteq \mathbb{R}^{2n}$. Such distributions show up often in cryptographic constructions (see, e.g., [LPR13]), and often that lattice is the (embedding of the) ring of integers R . For background on the discrete Gaussian distribution and the smoothing parameter, see, e.g., [MR04]. In order to apply Lemma 5.5 to this distribution, take X to be the continuous Gaussian D_r for some $r \geq 100n\eta_\varepsilon(L)$, and Y the discrete Gaussian $D_{L-X,s}$ over the coset $L - X$ of parameter $s = \eta_\varepsilon(L)$ for some negligible parameter ε . Using Banaszczyk's result [Ban93] we have that with all but exponentially small probability in n , $\|Y\|_2 \leq \sqrt{2n}\eta_\varepsilon(L) \leq r/(60\sqrt{n})$. Moreover, by the lemma below, the distribution of $Z = X + Y$ is within negligible statistical distance of the discrete Gaussian distribution $D_{L,r'}$ for $r' = (r^2 + \eta_\varepsilon(L)^2)^{1/2}$. We therefore see that the condition in Theorem 4.1 holds for the discrete Gaussian distribution $D_{L,r'}$ for any lattice L and any $r' > 200n\eta_\varepsilon(L)$.

Lemma 5.6 (Special case of [Pei10, Theorem 3.1]). *Let L be a lattice and $r, s > 0$ be such that $s \geq \eta_\varepsilon(L)$ for some $\varepsilon \leq 1/2$. Then if we choose \mathbf{x} from the continuous Gaussian D_r and then choose \mathbf{y} from the discrete Gaussian $D_{L-\mathbf{x},s}$ then $\mathbf{x} + \mathbf{y}$ is within statistical distance 8ε of the discrete Gaussian $D_{L,(r^2+s^2)^{1/2}}$.*

6 Shortest Generators of Principal Ideals and an SVP Algorithm

In a principal ideal, scaled to have algebraic norm 1, how long (in Euclidean norm) can the shortest generator be? In this section we provide lower and upper bounds showing that for cyclotomics of prime-power index m , the answer is $\exp(\tilde{\Theta}(\sqrt{m}))$, where the $\tilde{\Theta}$ hides polylogarithmic factors. By contrast, the minimum distance (i.e., the length of a shortest nonzero vector) of any ideal of unit norm is bounded by $\Omega(\sqrt{m})$ and $O(m)$.

The above bounds on the shortest generator follow directly from an analysis of the *covering radius* of the log-unit lattice Λ (and its sublattice $\text{Log } C$), in the ℓ_∞ norm. In fact, the proofs demonstrate more: the lower bound holds for “almost all” principal ideals of unit norm, and the upper bound is algorithmic in the following sense: given an arbitrary generator (which can be found using the quantum PIP algorithm of [BS15, BS16]), we can efficiently find a generator satisfying the bound, which in particular is a $\exp(\tilde{O}(\sqrt{m}))$ -approximate shortest vector in the ideal.

Throughout this section we let m be a prime power, and let $n := |G| = \varphi(m)/2 = \Theta(m)$. Let H be the subspace of \mathbb{R}^n orthogonal to the all-1 vector. Define the covering radius of a lattice \mathcal{L} with respect to the ℓ_p norm as

$$\mu^{(p)}(\mathcal{L}) = \max_{\mathbf{x} \in \text{span}(\mathcal{L})} \min_{\mathbf{v} \in \mathcal{L}} \|\mathbf{x} - \mathbf{v}\|_p.$$

6.1 Covering Radius Upper Bound and an SVP Algorithm

Theorem 6.1. *There is an efficient randomized algorithm that given any vector $\mathbf{x} \in H$ outputs a vector $\mathbf{v} \in \text{Log } C$ such that $\|\mathbf{x} - \mathbf{v}\|_\infty = O(\sqrt{m \log m})$ with high probability.*

Before giving the proof, we mention some implications of the theorem. First, using the fact that $\text{Log } C$ is a sublattice of Λ , we immediately get the following corollary regarding the covering radii of these lattices.

Corollary 6.2. *For a prime power m , $\mu^{(\infty)}(\Lambda) \leq \mu^{(\infty)}(\text{Log } C) \leq O(\sqrt{m \log m})$.*

We remark that this corollary can also be obtained directly from Lemma 6.6 below and the non-trivial result of Banaszczyk and Szarek [BS97] (see also [Ban98]). We also note that if the Komlós conjecture is true, then the $\sqrt{\log m}$ factor in the corollary can be removed.

It follows immediately from the corollary and the definition of the logarithmic embedding that any principal ideal of algebraic norm 1 has a generator whose Euclidean norm is at most $\exp(O(\sqrt{m \log m}))$. This observation leads to an efficient quantum algorithm providing a non-trivial approximation to SVP in principal ideals, as described in the theorem below.

Corollary 6.3. *There is an efficient algorithm that given $g \in K$ of algebraic norm 1 outputs a unit $u \in C$ such that $g \cdot u^{-1}$ has Euclidean norm at most $\exp(O(\sqrt{m \log m}))$.*

Proof. Apply the algorithm from Theorem 6.1 with the input $\mathbf{x} = \text{Log } g \in H$ to find $\mathbf{v} \in \text{Log } C$ such that $\|\mathbf{x} - \mathbf{v}\|_\infty = O(\sqrt{m \log m})$. Find coefficients $a_j \in \mathbb{Z}$ such that $\mathbf{v} = \sum a_j \mathbf{b}_j$ and output $u = \prod b_j^{a_j}$. The claim follows from the observation that $\text{Log}(g \cdot u^{-1}) = \mathbf{y} - \mathbf{v}$. \square

Theorem 6.4. *There is an efficient quantum algorithm that approximates SVP on principal ideal lattices in cyclotomics of prime-power index m to within approximation factor $2^{O(\sqrt{m \log m})}$.*

Proof. As in the proof of Theorem 4.1, for simplicity we ignore issues of precision; see the discussion at the end of Section 4. We are given a principal ideal I , and can assume without loss of generality that I has

algebraic norm 1, by scaling. First use the efficient quantum algorithm of Biasse and Song [BS15] to recover a generator g of I . Next, apply Corollary 6.3 to obtain another generator $g' = g \cdot u^{-1}$ of I with Euclidean norm $\exp(O(\sqrt{m \log m}))$, and output g' . This output vector is sufficiently short since for any ideal I of algebraic norm 1, by the arithmetic mean-geometric mean inequality we have $\lambda_1(I) = \Omega(\sqrt{m})$. \square

For the proof of Theorem 6.1, we need a simple probabilistic lemma, as well as a bound on the norm of the \mathbf{b}_j . For $\alpha \in [0, 1]$, define $S(\alpha)$ as the unique probability distribution on support $\{\alpha, \alpha - 1\}$ with expectation 0 (i.e., it assigns probability $1 - \alpha$ to α and probability α to $\alpha - 1$).

Lemma 6.5. *Let \mathbf{A} be an $n \times n$ matrix all of whose rows have Euclidean norm at most $T > 0$, and let $\alpha_1, \dots, \alpha_n \in [0, 1]$ be arbitrary. Let x_1, \dots, x_n be independent with x_i distributed as $S(\alpha_i)$, and let $\mathbf{x} = (x_1, \dots, x_n)$. Then with probability $\Omega(1/\sqrt{n})$, both*

$$\|\mathbf{Ax}\|_\infty \leq O(T\sqrt{\log n}) \quad \text{and} \quad \left| \sum x_i \right| \leq O(1) .$$

Proof. Since $S(\alpha)$ is bounded, it is a subgaussian random variable of constant subgaussian norm. (See [Ver12, Section 5.2.3] for the definition and properties of subgaussian random variables.) Because the sum of independent subgaussian random variables is also subgaussian (see [Ver12, Lemma 5.9]), $(\mathbf{Ax})_i$ has subgaussian norm $O(T)$ for every $i = 1, \dots, n$. Therefore, for a large enough universal constant $C > 0$,

$$\Pr[|(\mathbf{Ax})_i| > CT\sqrt{\log n}] = O(1/n^2) ,$$

and by a union bound we get

$$\Pr[\|\mathbf{Ax}\|_\infty > CT\sqrt{\log n}] = O(1/n) . \tag{8}$$

Next, by the Berry-Esseen theorem (see, e.g., [O'D14, Section 5.2]), since the x_i have expectation 0 and bounded second and third moments, the probability that $|\sum x_i| = O(1)$ is $\Omega(1/\sqrt{n})$. Together with Eq. (8) and the union bound, this completes the proof. \square

Lemma 6.6. *Let m be a prime power. Then for all $j \in G$, $\|\mathbf{z}_j\| = O(\sqrt{m})$, where \mathbf{z}_j are the vectors defined in Eq. (3).*

Proof. Notice that

$$\begin{aligned} \|\mathbf{z}_j\|^2 &= \sum_{i \in G} \log^2 |\omega^{ij} - 1| = \sum_{i \in G} \log^2 |\omega^i - 1| \\ &= \sum_{i \in G} \log^2 |2 \sin(\pi i/m)| \leq \sum_{i=1}^{\lfloor m/2 \rfloor} \log^2 (2 \sin(\pi i/m)) \\ &= \sum_{i=1}^{\lfloor m/2 \rfloor} f(i/m) , \end{aligned} \tag{9}$$

where $f : [0, 1/2] \rightarrow \mathbb{R}$ is given by $f(x) = \log^2(2 \sin(\pi x))$. Since $f(x) \leq \log 2$ for $1/6 \leq x \leq 1/2$ (recall that $\sin(\pi/6) = 1/2$), the contribution to the sum in Eq. (9) coming from $i > \lfloor m/6 \rfloor$ is at most $O(m)$. It

therefore suffices to consider the contribution coming from $i \in \{1, \dots, \lfloor m/6 \rfloor\}$. Since $\sin(\pi x) \geq 2x$ for $0 \leq x \leq 1/2$ (as follows from the concavity of sine on $[0, \pi/2]$), that contribution satisfies

$$\sum_{i=1}^{\lfloor m/6 \rfloor} f(i/m) \leq \sum_{i=1}^{\lfloor m/6 \rfloor} \log^2(4i/m) \leq m \int_0^{1/6} \log^2(4x) dx = O(m),$$

the last equality following from

$$\int_0^y \log^2(x) dx = y(\log^2 y - 2 \log y + 2). \quad \square$$

Proof of Theorem 6.1. Given any $\mathbf{y} \in H$, find real coefficients $(a_j)_{j \in G \setminus \{1\}}$ such that $\mathbf{y} = \sum a_j \mathbf{b}_j$. For $j \in G \setminus \{1\}$, let $\alpha_j = (a_j \bmod 1) \in [0, 1)$ be the fractional part of a_j , and let x_j be independent random variables distributed like $S(\alpha_j)$. The algorithm outputs $\mathbf{u} = \sum (a_j - x_j) \mathbf{b}_j$. Notice that $\mathbf{u} \in \text{Log } C$ as desired. To analyze the distance of \mathbf{u} from \mathbf{y} , for convenience let x_1 be an independent random variable distributed like $S(0)$ (so $x_1 = 0$ always). Recalling that $\mathbf{b}_j = \mathbf{z}_j - \mathbf{z}_1$, write

$$\mathbf{y} - \mathbf{u} = \sum_{j \in G} x_j (\mathbf{z}_j - \mathbf{z}_1) = \sum_{j \in G} x_j \mathbf{z}_j - \left(\sum_{j \in G} x_j \right) \mathbf{z}_1,$$

and so by the triangle inequality

$$\begin{aligned} \|\mathbf{y} - \mathbf{u}\|_\infty &\leq \left\| \sum_{j \in G} x_j \mathbf{z}_j \right\|_\infty + \left| \sum_{j \in G} x_j \right| \cdot \|\mathbf{z}_1\|_\infty \\ &\leq \left\| \sum_{j \in G} x_j \mathbf{z}_j \right\|_\infty + \left| \sum_{j \in G} x_j \right| \cdot O(\sqrt{m}), \end{aligned}$$

where we used the trivial bound $\|\mathbf{z}_1\|_\infty \leq \|\mathbf{z}_1\|_2$ and applied Lemma 6.6.⁷ We now apply Lemma 6.5 to the matrix \mathbf{Z} whose columns are the \mathbf{z}_j . Since \mathbf{Z} is G -circulant, the Euclidean norms of all its rows and columns are the same, and by Lemma 6.6 are $O(\sqrt{m})$. We therefore obtain that with probability $\Omega(1/\sqrt{n})$,

$$\|\mathbf{y} - \mathbf{u}\|_\infty \leq O(\sqrt{m \log n}) + O(\sqrt{m}) = O(\sqrt{m \log m}),$$

as desired. The success probability can be amplified by repetition. □

6.2 Covering Radius Lower Bound

Let $h' := (h^+)^{1/(n-1)}$, which we recall is conjectured to be constant.

Theorem 6.7. *For a prime power m , the log-unit lattice satisfies*

$$\mu^{(1)}(\Lambda) \geq \Omega(m^{3/2}/(h' \log m)).$$

⁷In fact, $\|\mathbf{z}_1\|_\infty = O(\log m)$, but we do not need this.

Since any vector $\mathbf{v} \in \mathbb{R}^n$ whose coordinates sum to zero (i.e., $\mathbf{v} \in H$) must have a coordinate that is at least $\|\mathbf{v}\|_1/(2n)$, we obtain that there exists a principal ideal of algebraic norm 1 whose generators all have Euclidean norm at least $\exp(\Omega(m^{1/2}/(h' \log m)))$. In fact, the proof shows that a “random principal ideal,” i.e., one corresponding to a uniformly random coset of the log-unit lattice, has this property with overwhelming probability.⁸

Proof. Using Lemma 6.8 below,

$$(\det(\text{Log } C))^{1/(n-1)} = \Omega(m^{1/2}/\log m) .$$

Since $\det(\Lambda) = \det(\text{Log } C)/h^+$,⁹

$$(\det(\Lambda))^{1/(n-1)} = \Omega(m^{1/2}/(h' \log m)) .$$

The theorem now follows from the fact that

$$\text{vol}(B_1^n \cap H) \leq \sqrt{n} \cdot 2^{n-1}/(n-1)! = O(1/n)^{n-1} ,$$

where $B_1^n := \{\mathbf{x} \in \mathbb{R}^n : \|\mathbf{x}\|_1 \leq 1\}$. To prove this inequality, notice that (1) the volume of B_1^{n-1} is $2^{n-1}/(n-1)!$, (2) the projection of $B_1^n \cap H$ on the first $n-1$ coordinates is contained in B_1^{n-1} , and (3) this projection shrinks volumes by \sqrt{n} , as can be seen by computing its Jacobian. \square

Lemma 6.8. *The determinant of $\text{Log } C$ satisfies*

$$\det(\text{Log } C)^{1/(n-1)} = \Omega(\sqrt{m}/\log m) .$$

Proof. Recall from the proof of Lemma 3.2 that the \mathbf{b}_j^\vee are the projection of \mathbf{z}_j^\vee orthogonal to $\mathbf{1}$. The $|G|$ -dimensional full-rank lattice generated by $\{\mathbf{z}_j^\vee\}_{j \in G}$ has determinant

$$|\det(\mathbf{Z}^{-t})| = \prod_{\chi \in \widehat{G}} |\lambda_\chi^{-1}| .$$

Next, notice that the shortest vector in the intersection of this lattice with the span of $\mathbf{1}$ is $\mathbf{Z}^{-t}\mathbf{1} = \lambda_1^{-1}\mathbf{1}$, whose Euclidean norm is $\lambda_1^{-1}\sqrt{|G|}$. Therefore, the dual of $\text{Log } C$, which is the projection of this lattice orthogonally to $\mathbf{1}$, has determinant

$$|G|^{-1/2} \prod_{\chi \in \widehat{G} \setminus \{1\}} |\lambda_\chi^{-1}| ,$$

and therefore

$$\begin{aligned} \det(\text{Log } C) &= |G|^{1/2} \prod_{\chi \in \widehat{G} \setminus \{1\}} |\lambda_\chi| \\ &= |G|^{1/2} \prod_{\chi \in \widehat{G} \setminus \{1\}} \left| \frac{1}{2} \cdot f_\chi^{1/2} \cdot L(1, \chi) \right| , \end{aligned}$$

⁸Making this precise requires a bit more effort. We omit the details.

⁹We note that $2^{n-1} \det(\Lambda)/\sqrt{n}$ is known as the *regulator*, and a bound similar to what we obtain here can be derived from the Brauer-Siegel theorem [Was97, Page 43]. This leads to a bound that is both somewhat weaker and ineffective.

where we used Eq. (5). Using Theorem 2.6, we get that

$$L := \prod_{\chi \neq 1} |L(1, \chi)| = \Omega((\log m)^{-(n-1-q)} \cdot p^{-q/2})$$

where q denotes the number of quadratic characters modulo m , i.e., $q = 3$ if $p = 2$ (and $k \geq 2$), and $q = 1$ for odd primes p (see [MV06, Section 9.3]). We conclude that

$$L^{1/(n-1)} = \Omega(1/\log m). \quad (10)$$

Next, consider $F = \prod_{\chi \in \hat{G} \setminus \{1\}} f_\chi$. For each $0 < j \leq k$, there are exactly $\varphi(p^j) - \varphi(p^{j-1})$ characters of conductor $f_\chi = p^j$. This leads to

$$\begin{aligned} \frac{\log F}{\log p} &= \sum_{j=1}^k j(\varphi(p^j) - \varphi(p^{j-1})) \\ &= k\varphi(p^k) - \sum_{j=0}^{k-1} \varphi(p^j) \\ &= kn - (p-1) \sum_{j=0}^{k-2} p^j - 1 = kn - p^{k-1}, \end{aligned}$$

and we conclude that

$$F = m^{n(1 - \frac{1}{k(p-1)})} = \Omega(m)^n. \quad (11)$$

Combining (10) and (11) completes the proof. \square

A Proof of Theorem 2.8

Proof. First, Corollary 4.13 of [Was97] gives that $\mathbb{Z}[\zeta]^*$ is generated by $\mathbb{Z}[\zeta + \bar{\zeta}]^*$ and ζ , so it follows that

$$\Lambda = \text{Log } \mathbb{Z}[\zeta]^* = \text{Log } \mathbb{Z}[\zeta + \bar{\zeta}]^*,$$

since the kernel of Log is the group $\{\pm 1\} \cdot U$.

Next, recall that the group of *cyclotomic units* is defined as $C = A \cap R^*$. We define the group of *real cyclotomic units* as $C^+ = A \cap \mathbb{Z}[\zeta + \bar{\zeta}]^*$. The analogue of Lemma 2.7 for the real cyclotomic units, also included in Lemma 8.1 of [Was97], says that the group C^+ of real cyclotomic units is generated by -1 and $\zeta^{(1-j)/2} \cdot b_j$. So as above, we obtain that

$$\text{Log } C = \text{Log } C^+.$$

The theorem then follows from the sequence of equalities

$$[\Lambda : \text{Log } C] = [\text{Log } \mathbb{Z}[\zeta + \bar{\zeta}]^* : \text{Log } C^+] = [\mathbb{Z}[\zeta + \bar{\zeta}]^* : C^+] = h^+,$$

where the second equality follows from $\ker(\text{Log}) \cap C^+ = \ker(\text{Log}) \cap \mathbb{Z}[\zeta + \bar{\zeta}]^* (= \{\pm 1\})$, and the third equality is Theorem 8.2 of [Was97]. \square

B Numeric Data

The previous sections established *asymptotic* bounds related to the log-embeddings of the cyclotomic units. Figure 1 gives concrete numeric data for several practical (and even impractical) choices of cyclotomic fields. This data confirms that the method works in practice.

$k (m = 2^k)$	6	7	8	9	≥ 10
$\ \mathbf{b}_j^\vee\ ^{-1}$	5.04	8.56	14.69	25.71	≥ 45.85

$k (m = 3^k)$	4	5	≥ 6
$\ \mathbf{b}_j^\vee\ ^{-1}$	5.72	13.65	≥ 34.04

$k (m = 5^k)$	3	4	≥ 5
$\ \mathbf{b}_j^\vee\ ^{-1}$	10.04	36.43	≥ 143

Figure 1: Lower bounds on the inverse lengths of the dual vectors \mathbf{b}_j^\vee defined in Section 3, for various cyclotomics of prime-power index. Larger values correspond to larger decoding distances for the log-embedding of the cyclotomic units.

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