TWISTERS AND SIGNED FUNDAMENTAL DOMAINS FOR NUMBER FIELDS

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Abstract. We give a signed fundamental domain for the action on $\mathbb{R}_{+}^{r_1} \times \mathbb{C}^{r_2}$ of the totally positive units $E_+$ of a number field $k$ of degree $n = r_1 + 2r_2$ which we assume is not totally complex. Here $r_1$ and $r_2$ denote the number of real and complex places of $k$ and $\mathbb{R}_{+}$ denotes the positive real numbers. The signed fundamental domain consists of $n$-dimensional $k$-rational cones $C_\alpha$, each equipped with a sign $\mu_\alpha = \pm 1$, with the property that the net number of intersections of the cones with any $E_+$-orbit is 1.

The cones $C_\alpha$ and the signs $\mu_\alpha$ are explicitly constructed from any set of fundamental totally positive units and a set of $3^{r_2}$ "twisters," i.e. elements of $k$ whose arguments at the $r_2$ complex places of $k$ are sufficiently varied. Introducing twisters gives us the right number of generators for the cones $C_\alpha$ and allows us to make the $C_\alpha$ turn in a controlled way around the origin at each complex embedding.

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1. Introduction

The usual embedding of a number field $k$ into a Euclidean space $V$ gives rise to an action of the units of $k$ on $V$. Good fundamental domains for this action are important in the study of abelian $L$-functions. For totally real fields, Shintani [Sh1] showed in 1976 the existence of fundamental domains consisting of a finite number of $k$-rational polyhedral cones, now known as Shintani cones. A few years later, in a posthumous and rarely cited work [Sh2], Shintani extended this to all number fields.

Shintani’s papers gave no practical procedure to construct his cones, or even to estimate how many cones were needed. In the late 1980’s Colmez [Co] showed for totally real fields the existence of certain special subgroups of the units for which he could explicitly construct Shintani-type fundamental domains for the action of this subgroup on $V$. This was a significant theoretical advance, but it was not effective since no practical procedure is known for producing Colmez’s special units, except in the quadratic or cubic case [DF1].

A few years ago Charollois, Dasgupta and Greenberg [CDG], and independently Diaz y Diaz and Friedman [DF2], found a way around this non-effectiveness for totally real fields by introducing signed fundamental domains. Espinoza [Es] then found effective signed fundamental domains for number fields having exactly one complex place.

Signed fundamental domains can be naturally defined if one defines fundamental domains using characteristic functions. Indeed, a set of subsets $\{C_\alpha\}_{\alpha \in J}$ of a space $Y$, on which a countable group $G$ acts, is a fundamental domain if

$$\sum_{\alpha \in J} \sum_{\varepsilon \in G} \chi_{C_\alpha}(\varepsilon \cdot y) = 1 \quad (\forall y \in Y),$$

where $\chi_{C_\alpha}$ is the characteristic function of $C_\alpha$. A signed fundamental domain is a finite list $\{C_\alpha\}_{\alpha \in J}$ of subsets of $Y$ and a corresponding list of signs $\mu_\alpha = \pm 1$ such that

$$\sum_{\alpha \in J} \mu_\alpha \sum_{\varepsilon \in G} \chi_{C_\alpha}(\varepsilon \cdot y) = 1 \quad (\forall y \in Y).$$

For technical reasons [DF2 Lemma 5], we also require that the cardinality of $C_\alpha \cap (G \cdot y)$ be bounded independently of $y \in Y$.

Before going into details, we outline the difficulties that appear with Shintani cones when $k$ is not totally real. Let $k$ be a number field of degree $n = r_1 + 2r_2$ having $r_1$ real places and $r_2$ pairs of complex conjugate embeddings. The most obvious problem is that we no longer have $n$ natural generators for the $n$-dimensional Shintani cones. In the totally real case, following Colmez, we can use $1 \in k$ and $n-1$ independent units of $k$ to generate the cones, but each complex case leaves us a unit short of the $n$ generators that we need. Thus, we must introduce one new generator for each complex place. An additional difficulty is that $\mathbb{R}^{r_1}_+ \times \mathbb{C}^{r_2}$, while it is a cone, is not convex if $r_2 > 0$. This means that $n$ independent vectors are liable to generate a cone including (nonzero) points outside $\mathbb{R}^{r_1}_+ \times \mathbb{C}^{r_2}$, for example where one complex coordinate vanishes. We choose the new generators for the cones so as to force all of them inside convex subsets of $\mathbb{R}^{r_1}_+ \times \mathbb{C}^{r_2}$. These generators we call twisters, as their arguments at the complex places are chosen so as to twist the generators into a convex conical sector.
The approach to signed fundamental domains in [DF2] and here can be summarized in the following commutative diagram of topological spaces

\[
\begin{array}{ccc}
\mathbb{X} \times \mathbb{R} & \xrightarrow{g} & \mathbb{R}_{+}^{n} \times \mathbb{C}^{*r_2} \\
\downarrow \pi & & \downarrow \pi \\
\tilde{T} & \xrightarrow{F} & T
\end{array}
\]

(1)

We begin by explaining the vertical arrow on the right. Suppose we are given totally positive independent units \(\varepsilon_1, \ldots, \varepsilon_r\) generating a subgroup \(E\) of finite index in the units of \(k\). Thus \(E\) acts on \(\mathbb{R}_{+}^{n} \times \mathbb{C}^{*r_2}\), where \(\mathbb{R}_{+}\) denotes the multiplicative group of positive real numbers. Let \(T = (\mathbb{R}_{+}^{n} \times \mathbb{C}^{*r_2})/E\) be the quotient manifold and \(\pi: \mathbb{R}_{+}^{n} \times \mathbb{C}^{*r_2} \to T\) the natural map.

It is well-known that \(T\) is homeomorphic to the product of an \((n-1)\)-torus with \(\mathbb{R}\). This is made explicit by the left vertical arrow in (1) and the maps \(g\) and \(G\), in the following sense. The standard (additive) model for \(\mathbb{R}_{+}^{n} \times \mathbb{C}^{*r_2}\) is of limited use because of its complicated geometry. In particular, it is difficult to describe the intersection of \(T\) with fractional ideals of \(k\), a vital step in Shintani’s treatment of \(L\)-functions.

To remedy this, for totally real fields Colmez deformed \(g\) to a new and simpler function \(f\) so that its image \(f(\mathbb{X} \times \mathbb{R})\) is a union of \(k\)-rational polyhedral cones. From our present standpoint, the work of Colmez [Co] can be described as follows.

Take the fundamental domain \(\mathbb{X} = [0,1]^{n-1}\) for the lattice \(\Lambda := \mathbb{Z}^{n-1} \subset \mathbb{R}^{n-1}\). There is a well-known decomposition, parametrized by the symmetric group \(S_{n-1}\), of the hypercube into simplices \(\mathbb{X}_\alpha\) [DF2 eq. (19)]. For each \(\alpha \in S_{n-1}\), let \(A_\alpha: \mathbb{X}_\alpha \to \mathbb{R}_{+}^{n}\) be the unique affine function which on each vertex \(\kappa\) of \(\mathbb{X}_\alpha\) takes the value \(g(\kappa \times 0) \in \mathbb{R}_{+}^{n}\) (recall that Colmez only dealt with the totally real case). Then we can unambiguously define \(f: \mathbb{X} \times \mathbb{R} \to \mathbb{R}_{+}^{n}\) by \(f(x \times t) := e^t A_\alpha(x)\) where \(x \in \mathbb{X}_\alpha\), \(t \in \mathbb{R}\). As \(\mathbb{R}_{+}^{n}\) is convex, \(f\) takes values in \(\mathbb{R}_{+}^{n}\) and \(f(\mathbb{X}_\alpha \times \mathbb{R})\) is the cone \(\overline{C}_\alpha\) generated by the \(g(\kappa \times 0)\) as \(\kappa\) ranges over the vertices of \(\mathbb{X}_\alpha\). Colmez [Co] proved that if the cones \(\overline{C}_\alpha\) meet only along common faces, then \(\bigcup_\alpha C_\alpha\) is a fundamental domain for the action of \(E\) on \(\mathbb{R}_{+}^{n}\). Here \(C_\alpha\) is \(\overline{C}_\alpha\) minus some boundary faces.

Colmez’s proof is rather complicated, but it can be greatly simplified [DF2] by observing that the decomposition \(\mathbb{X} = \bigcup_\alpha \mathbb{X}_\alpha\) is good enough that \(f\) induces a map \(F: \tilde{T} \to T\) of the quotient manifolds in (1). One can then use topological degree theory to show that \(\bigcup_\alpha C_\alpha\) is a signed fundamental domain with weights \(\mu_\alpha\) given by the degree of \(f\) restricted to \(\mathbb{X}_\alpha \times \mathbb{R}\). If we add Colmez’s hypothesis that the
and assume we have chosen an integer \( N \) embedding. To have the smallest number of cones we should take \( N \varepsilon \). We also fix independent totally positive units \( V \).

Be a decomposition \( R_+^r \times C^{*r+2} \) is not convex, so to define \( f \) we must ensure that the generators of the cones lie in convex subsets of \( R_+^r \times C^{*r+2} \). Moreover, the decomposition \( \mathcal{X} = \bigcup_\alpha \mathcal{X}_\alpha \) must again allow \( f \) to descend to a map \( F \) of the quotient manifolds.

An additional difficulty is that the natural choice of \( g \) does not give cone generators in \( k \), as in general \( g(\kappa \times 0) \notin k \) for \( \kappa \) a vertex of \( \mathcal{X}_\alpha \). We fix this by modifying \( g \) slightly. Fortunately, the homotopy involved in formalizing this approximation does not alter topological degrees, and so this turns out to be a minor difficulty.

Espinoza \( [Es] \) obtained a signed fundamental domain for fields \( k \) with exactly one pair of complex embeddings. In this paper we extend the ideas there to all non-totally complex number fields. We exclude totally complex fields solely because in this case we have not been able to give a satisfactory description of the boundary faces that should be included in the signed fundamental domain. The reader will find in the next section a detailed description of the signed fundamental domain obtained.

As mentioned at the beginning of this paper, signed fundamental domains are useful for working with abelian \( L \)-functions. More precisely, as in \( [DF2] \), Cor. 6 and \( [Es] \), Cor. 3, using a signed fundamental domain one can explicitly write any abelian \( L \)-function as a finite linear combination of Shintani zeta functions \( [Sh1] \). The Shintani functions do not in general satisfy a functional equation of the usual kind, but they do satisfy a ladder of difference equations and are normalized by vanishing integrals \( [FR] \), eqs. 1.4 and 1.7. In a more geometric vein, in a forthcoming doctoral thesis Alex Capuñay gives a practical algorithm producing a true \( k \)-rational fundamental cone domain starting from a signed one.

2. Signed fundamental domain

We fix a number field \( k \) of degree \( [k : \mathbb{Q}] = n \), having \( r_1 \) real embeddings \( \tau_1, \ldots, \tau_{r_1} \) and \( r_2 \) pairs of conjugate complex embeddings

\[
\tau_{r_1+1}, \tau_{r_1+1}, \ldots, \tau_{r_1+r_2}, \tau_{r_1+r_2},
\]

which we use to embed \( k \) in \( \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \) by \( \gamma \rightarrow (\gamma^{(i)})_i \), where \( \gamma^{(i)} := \tau_i(\gamma) \) \((1 \leq i \leq r_1 + r_2)\). To save notation, we identify \( \gamma \in k \) with its image \( (\gamma^{(i)})_i \in \mathbb{R}^r \times \mathbb{C}^s \). We also fix independent totally positive units \( \varepsilon_1, \ldots, \varepsilon_r \) of \( k \), where \( r = r_1 + r_2 - 1 \), and assume we have chosen an integer \( N_j \geq 3 \) \((1 \leq j \leq r_2)\) for each complex embedding. To have the smallest number of cones we should take \( N_j = 3 \) for all \( j \).

2.1. Raising the dimension of a complex. An ordered \( p \)-complex \( X \) for us will be a decomposition

\[
X := \bigcup_{\alpha \in J} X_{\alpha, <\alpha},
\]

where the \( X_{\alpha, <\alpha} \subset V \) are ordered \( p \)-dimensional simplices in a \( p \)-dimensional real vector space \( V \). Thus, for each \( \alpha \) in the (possibly infinite) index set \( J \) we are given the set of vertices \( \text{Vt}(X_{\alpha}) \) of the \( p \)-simplex \( X_{\alpha} \) and a total ordering \( <_\alpha \) on \( \text{Vt}(X_{\alpha}) \).
We will later want our complexes to satisfy quite a few properties, but the above definition will do to identify a complex. We shall be loose with the notation and denote by $X$ both the underlying point set and the complex, i.e., its decomposition \( \mathcal{C} \). Similarly, we shall often write $X_n$ for both the simplex and the ordered simplex $X_n$.\( \star \)

Our purpose in this subsection is to construct a new ordered \((p + 1)\)-complex

\[
Y = Y(X, \omega, [M_1, M_2]) := \bigcup_{\gamma \in J} Y_{\gamma, \prec} \subset V \times \mathbb{R}
\]

from a given \( p \)-complex \( X = \bigcup_{\alpha \in J} X_{\alpha, \prec} \subset V \), a linear function \( \omega : V \rightarrow \mathbb{R} \) and an interval \([M_1, M_2]\). Here the \( M_i \) are integers and \( M_1 < M_2 \). In our application \( \omega \) will either vanish identically or be determined by the arguments of the units \( \epsilon_i \) at some complex embedding. The new ambient vector space is \( V \times \mathbb{R} \), and the new index set is

\[
J := \{(\alpha, v, \ell) \mid \alpha \in \mathcal{J}, v \in Vt(X_{\alpha}), \ell \in \mathbb{Z}, M_1 \leq \ell < M_2\}.
\]

If \( \mathcal{J} \) is a finite set, then so is \( J \) and its cardinality is

\[
|J| = (M_2 - M_1)(p + 1)|\mathcal{J}|.
\]

To define the simplex \( Y_\gamma \) for \( \gamma = (\alpha, v, \ell) \in J \) requires some preliminaries. Let \( A : V \rightarrow (0, 1] \) be the upper fractional part of \( \omega \), i.e., \( A(u) \in \mathbb{R} \) is uniquely determined by

\[
A(u) - \omega(u) \in \mathbb{Z}, \quad \quad 0 < A(u) \leq 1 \quad (u \in V).
\]

We use \( A \) to define a new total order \( \prec_A^\alpha \) on \( Vt(X_{\alpha}) \) by

\[
u \prec_A^\alpha u' \iff \left[ [A(u) < A(u')] \text{ or } [A(u) = A(u') \text{ and } u \prec u'] \right]
\]

for \( u, u' \in Vt(X_{\alpha}) \). Note that if \( \omega = 0 \) identically, then \( \prec_A^\alpha = \prec_\alpha \).

We now define \( Y_\gamma \) in \( \mathcal{J} \) for \( \gamma = (\alpha, v, \ell) \in J \). Order the vertices \( \{v_0, v_1, \ldots, v_p\} \) of \( X_{\alpha} \) so that \( v_0 \prec_A^\alpha v_1 \prec_A^\alpha \cdots \prec_A^\alpha v_p \). Since \( v \in Vt(X_{\alpha}) \) by definition \( \mathcal{J} \), there is a unique \( j = j_\gamma \) such that \( v = v_j \). Note that \( j \) depends on the order \( \prec_A^\alpha \). Let \( \{s_1, \ldots, s_t\} \) denote the convex hull of \( s_1, \ldots, s_t \). Then \( Y_\gamma \subset V \times \mathbb{R} \) is defined as

\[
Y_\gamma := [v_0 \times (A(v_0) - \omega(v_0) + \ell), v_1 \times (A(v_1) - \omega(v_1) + \ell), \ldots, v_j \times (A(v_j) - \omega(v_j) + \ell - 1), v_{j+1} \times (A(v_{j+1}) - \omega(v_{j+1}) + \ell - 1), \ldots, v_p \times (A(v_p) - \omega(v_p) + \ell - 1)]
\]

Note that vertices of \( Y_\gamma \) map to vertices of \( X_{\alpha} \) by the projection \( \pi_V : V \times \mathbb{R} \rightarrow V \), and that the coordinate we have added to each vertex is an integer (see \( \mathcal{J} \)).

Finally, the new ordering \( \prec_\gamma \) on the vertices of the new simplex \( Y_\gamma \) is defined by

\[
\rho \prec_\gamma \rho' \iff \left[ [\pi_V(\rho) \prec_A^\alpha \pi_V(\rho')] \text{ or } [\pi_V(\rho) = \pi_V(\rho') \text{ and } \pi_R(\rho') < \pi_R(\rho)] \right]
\]

where \( \pi_R : V \times \mathbb{R} \rightarrow \mathbb{R} \) is the projection onto the second factor. Note that \( \prec_\gamma \) is defined using the original order \( \prec_\alpha \) on the vertices of \( X_{\alpha} \), even though we used the modified order \( \prec_A^\alpha \) to construct \( Y_\gamma \).
2.2. The \((n - 1)\)-complex \(\mathfrak{X}\). We start from the trivial 0-complex
\[
X_0 := X_{O, \prec O} \subset \mathbb{R}^0,
\]
where \(\mathbb{R}^0 := \{0\}\) is the trivial vector space, the index set is \(\{O\}\) (or any one-element set), and the ordered 0-simplex \(X_{O, \prec O} = \{0\}\) is equipped with the trivial (empty) ordering \(\prec O\) on the single vertex 0. For \(1 \leq j \leq r := r_1 + r_2 - 1\), let \(\omega_{j-1} : \mathbb{R}^{j-1} \to \mathbb{R}\) be the trivial linear function \(\omega_{j-1}(x) := 0\), and define
\[
X_j := Y(X_{j-1}, \omega_{j-1}, [0, 1]) \subset \mathbb{R}^j \quad (1 \leq j \leq r),
\]
where \(Y\) was defined in (13). If \(k\) is totally real, so \(r = n - 1\), we are done constructing \(\mathfrak{X} := X_{n-1}\). Otherwise, we must carry out further steps, one for each complex place of \(k\). For \(1 \leq j \leq r_2\), let \(\omega_{r+j-1} : \mathbb{R}^{r+j-1} \to \mathbb{R}\) be given by
\[
\omega_{r+j-1}(x) := \frac{N_j}{2\pi} \sum_{\ell=1}^r x[\ell] \arg(\varepsilon_\ell^{(r_1+j)}), \quad (x = (x[1], x[2], ..., x[r+j-1])),
\]
where we recall that for each \(1 \leq j \leq r_2\) we have fixed an integer \(N_j \geq 3\). For the sake of definiteness, the arguments above are taken so that \(-\pi < \arg(z) \leq \pi\), but any branch would do as well. Define
\[
X_{r+j} := Y(X_{r+j-1}, \omega_{r+j-1}, [0, N_j]) \subset \mathbb{R}^{r+j} \quad (1 \leq j \leq r_2),
\]
with \(Y\) as in (13).

We have thus constructed an \((n - 1)\) ordered complex
\[
\mathfrak{X} = \bigcup_{\alpha \in \mathfrak{I}} \mathfrak{X}_\alpha := X_{n-1} \subset \mathbb{R}^{n-1} \quad (|\mathfrak{I}| = (n - 1)! \prod_{j=1}^{r_2} N_j),
\]
corresponding to \(j = r_2\) above. We have dropped the order \(\prec\) on \(\text{Vt}(\mathfrak{X}_\alpha)\) from our notation since, once \(\mathfrak{X}\) is constructed we will have no further interest in ordering the set of vertices
\[
\text{Vt}(\mathfrak{X}_\alpha) := \{v_{0,\alpha}, v_{1,\alpha}, ..., v_{n-1,\alpha}\} \subset \mathbb{Z}^{n-1}.
\]
However, we will use the fact the vertices \(v_{\ell,\alpha}\) have integral coordinates. This is clear since we started from the single vertex 0 of \(X_0\). As we noted after (8), in passing from \(X_{j-1}\) to \(X_j\) the new coordinate appended to a vertex is always integral.

2.3. The twister function \(\beta\). Recall that we have fixed \(r := r_1 + r_2 - 1\) independent totally positive units \(\varepsilon_1, ..., \varepsilon_r\) in the number field \(k\) and integers \(N_j \geq 3\) for \(1 \leq j \leq r_2\). We must now also fix “twisters” \(\beta(x)\), which are totally positive elements of \(k^*\) whose arguments at the various complex places are sufficiently close to those of certain roots of unity determined by \(x\). More precisely, choose a function \(\beta : \mathbb{Z}^{n-1} \to k^*\) with the following properties:

- \(\beta(x)\) is a totally positive element of \(k\).
- For \(x = (x[1], ..., x[n-1]) \in \mathbb{Z}^{n-1}\) and \(1 \leq j \leq r_2\), there is a \(t_j(x) \in \mathbb{R}\) such that
\[
\left| \frac{t_j(x)}{N_j} \right| < \frac{1}{4} \quad \frac{1}{2N_j}, \quad \beta(x)^{(j+r_1)} = \exp\left(2\pi i (x[j] + r_2) / N_j\right).
\]

\[\footnote{Although we will not need this, \(X_r\) is the well-known decomposition of the \(r\)-cube \([0, 1]^r\) into \(r!\) simplices determined by the order of the coordinates [DF2, eq. (19)].} \]
For example, if $N_j = 3$ this requires that, at the $(j+r_1)$-th embedding, the argument of $\beta(x)$ be no farther than $\pi/6$ from that of $\exp(2\pi ix[j+r]/3)$.

- We have

$$\beta(x + \lambda) = \beta(x) \quad (x \in \mathbb{Z}^{n-1}, \lambda \in \Lambda := \mathbb{Z}^r \times N_1 \mathbb{Z} \times \cdots \times N_r \mathbb{Z}).$$

Thus, the twist $\beta$ amounts to a function on the finite set $\mathbb{Z}^{n-1}/\Lambda$. Note that in (14) we can take $t_j(x + \lambda) = t_j(x)$. Twister functions exist by our assumption $N_j \geq 3$ and the density of $k$ in $\mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$

2.4. Signs. We need to compute three determinants to define the sign

$$\mu_\alpha := (-1)^{r_2(r_2-1)/2} \sign(\det(R) \det(V_\alpha) \det(W_\alpha)).$$

Although $R$ and $V_\alpha$ will prove to be invertible matrices, $W_\alpha$ may not be. Thus, $\mu_\alpha$ may take the values $\pm 1$ or $0$.

Recall that we have listed the embeddings $\tau_1$ of $k$ so that they are real for $1 \leq i \leq r_1$ and are complex conjugate pairs $\tau_i, \bar{\tau}_i$ for $r_1 < i \leq r_1 + r_2$. The $(r_1 + r_2) \times (r_1 + r_2)$ matrix $R = (r_{ij})$ is defined by

$$r_{ij} := \begin{cases} 1 & \text{if } i = 1, \\ \log |\varepsilon_{i-1}^{(j)}| & \text{if } 2 \leq i \leq r_1 + r_2. \end{cases} \quad (1 \leq i, j \leq r_1 + r_2).$$

Actually, $|\det(R)| = 2^{-r_2}n \Reg(\varepsilon_1, \ldots, \varepsilon_r)$, where $\Reg$ is the regulator of the units $\varepsilon_i$, but we care here only for the sign of $\det(R)$.

Define $V_\alpha$ as the $(n-1) \times (n-1)$ matrix whose $i$-th column is $v_{i,\alpha} - v_{0,\alpha} \in \mathbb{Z}^{n-1}$ $(1 \leq i \leq n-1)$. Here $V(\mathfrak{x}_\alpha) = \{v_{0,\alpha}, v_{1,\alpha}, \ldots, v_{n-1,\alpha}\} \subset \mathbb{Z}^{n-1}$ was given in (12) with the complex $\mathfrak{x}$. To define the matrix $W_\alpha$ in (13), let

$$w_\ell = w_{\ell,\alpha} := \beta(v_{\ell,\alpha}) \prod_{j=1}^r \varepsilon_{j,\alpha}^{v_{\ell,\alpha}[j]} \quad (0 \leq \ell \leq n-1).$$

Thus $w_\ell \in k^\ast$. Define $W_\alpha$ as the real $n \times n$ matrix with $(\ell + 1)$-th row

$$\tau_1(w_\ell), \tau_2(w_\ell), \ldots, \tau_n(w_\ell),$$

$$\Re(\tau_{r_1+1}(w_\ell)), \Im(\tau_{r_1+1}(w_\ell)), \ldots, \Re(\tau_{r_1+r_2}(w_\ell)), \Im(\tau_{r_1+r_2}(w_\ell))$$

for $0 \leq \ell \leq n-1$.

2.5. Cones. For $\alpha \in \mathfrak{J}$ as in (12), let

$$C_\alpha := \left\{ \sum_{\ell=0}^{n-1} x_{\ell} w_{\ell,\alpha} \big| x_{\ell} \geq 0 \text{ for } 0 \leq \ell \leq n-1 \right\} - \{0\},$$

where $w_{\ell,\alpha} \in k \subset \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ was defined in (18). If $w_{0,\alpha}, \ldots, w_{n-1,\alpha}$ is not an $\mathbb{R}$-basis of the real vector space $\mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$, i.e., if $\mu_\alpha = 0$, we will not define the

$^2$ $\beta(x)$ can be computed by taking a $\mathbb{Q}$-basis $\gamma_1, \ldots, \gamma_n$ of $k \subset \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$, finding for each $x \in \mathbb{Z}^{n-1}$ with $0 \leq x[j] < N_j$ $(1 \leq j \leq r_2)$, rational solutions $a_{\ell} = a_{\ell}(x) \quad (1 \leq \ell \leq n)$ to the approximate equality

$$(1, \ldots, 1, \exp(2\pi ix[r_1+1]/N_1), \ldots, \exp(2\pi ix[n-1]/N_{r_2})) \approx \sum_{\ell=1}^n a_{\ell} \gamma_{\ell},$$

and letting $\beta(x) := \sum_{\ell=1}^n a_{\ell} \gamma_{\ell}$. Then extend $\beta$ to all $x \in \mathbb{Z}^{n-1}$ by periodicity (13).

$^3$ Note that we removed the origin in (19). A great part of our efforts will be directed to showing that $C_\alpha$ is contained in $\mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$. Here the difficulty is in ensuring that the complex components do not vanish.
subset $C_\alpha$ of $\overline{\mathcal{C}}$. If $\mu_\alpha \neq 0$, we can write $e_1 = (1, 0, \ldots, 0) \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ uniquely as $e_1 = \sum_{\ell=0}^{n-1} y_{\ell,\alpha} w_{\ell,\alpha}$, where $y_{\ell,\alpha} \in \mathbb{R}$. We shall prove (see Lemma 24) that $y_{\ell,\alpha} \neq 0$ for $0 \leq \ell \leq n - 1$. Define the cones
\begin{equation}
C_\alpha := \left\{ \sum_{\ell=0}^{n-1} x_{\ell} w_{\ell,\alpha} \middle| x_{\ell} \in R_{\ell,\alpha} \right\}, \quad R_{\ell,\alpha} := \begin{cases} [0, \infty) & \text{if } y_{\ell,\alpha} > 0, \\ (0, \infty) & \text{if } y_{\ell,\alpha} < 0. \end{cases}
\end{equation}
Note that $C_\alpha$ is the open $n$-dimensional cone generated by the $w_{\ell,\alpha}$, together with some of its boundary faces.

We can now state our main result.

**Theorem 1.** Let independent totally positive units $\varepsilon_1, \ldots, \varepsilon_r$ and a twister function $\beta$ be given as in (23) for a number field $k$, let $E := (\varepsilon_1, \ldots, \varepsilon_r)$ be the subgroup of the units of $k$ generated by the $\varepsilon_i$, and assume that $k$ is not totally complex. Then the cones $C_\alpha \subset \mathbb{G}$, defined in (20), (12) and (16), is a signed fundamental domain for the action of $E$ on $\mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ consisting of $k$-rational signed cones.

Thus, the cones $C_\alpha$ have generators $w_{\ell,\alpha} \in k$ defined in (12), and for any $x \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ we have
\begin{equation}
\sum_{\alpha \in \mathcal{J}} \sum_{\mu_\alpha \neq 0} \varepsilon \in \mathcal{E} \chi_{C_\alpha}(\varepsilon x) = 1,
\end{equation}
where $\chi_{C_\alpha}$ is the characteristic function of $C_\alpha$. Furthermore, $\chi_{C_\alpha}(\varepsilon x) = 0$ except for $\varepsilon$ in a finite set of cardinality bounded independently of $x$.

We recall that in (12) there is a free choice of integers $N_j \geq 3$ for $1 \leq j \leq r_2$ and that the number of cones $C_\alpha$ is at most $(n - 1)! \prod_j N_j$, where $n = [k : \mathbb{Q}]$. If we pick all $N_j = 3$, then there are at most $3^{r_2} \cdot (n - 1)!$ cones.

If $k$ is totally complex, we still prove (21), but only for $x$ outside the $E$-orbit of the boundary of all $\overline{\mathcal{C}}$. The excluded set has Lebesgue measure 0, but is still unfortunate for the calculation of abelian $L$-functions.

There are two very different parts to the proof of Theorem 1 The first (see (23)) consists of showing that if a complex $X$ has a number of properties with respect to a lattice $\Lambda$, then so does the complex $Y(X, \omega, [M_1, M_2])$ with respect to the lattice $\Lambda \times (M_2 - M_1)\mathbb{Z}$. This allows us to construct inductively an $(n - 1)$-complex $\mathcal{X}$ and a function $f : \mathcal{X} \times \mathbb{R} \to \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}$ whose image gives the cones in the signed fundamental domain. The second part of the proof (see (24) is mainly a calculation of certain global and local topological degrees associated to $f$. As in [DF2] [ES], degrees enter because Theorem [24] can be interpreted as an instance of the local-global principle on suitable manifolds.

### 3. Lattice-adapted ordered simplicial complexes

#### 3.1. Affine preliminaries

Let $V$ be a real vector space and $\{v_0, \ldots, v_p\} \subset V$ a finite subset. It is called affinely independent if for a fixed $j$ the set $\{v_i - v_j\}_{0 \leq i \leq p, i \neq j}$ is linearly independent. This notion does not depend on the choice of $j$. If $p = 0$, any $v_0 \in V$ is affinely independent.

The convex hull $S$ of $\{v_0, \ldots, v_p\}$ is
\begin{equation}
S = [v_0, v_1, \ldots, v_p] := \left\{ \omega = \sum_{j=0}^{p} t_j v_j \middle| t_j \geq 0, \sum_{j=0}^{p} t_j = 1 \right\}.
\end{equation}
We call $S$ a simplex if the $v_j$ are affinely independent. Then $\text{Vt}(S) := \{v_0, v_1, \ldots, v_p\}$, its set of vertices, is uniquely determined by the point set $S$. If we wish to note the dimension of $S$, we call it a $p$-simplex. An $\ell$-face, or simply a face, of $S$ is an $\ell$-simplex $K$ such that $\text{Vt}(K) \subset \text{Vt}(S)$.

The $t_j$ in (22) are called the barycentric coordinates of $\omega$ and $\sum_{j=0}^{p} t_j v_j$ is called its barycentric expansion (with respect to $S$). If $S$ is a simplex we write $\text{SpVt}(\omega) = \text{SpVt}(\omega; S)$ for the set of spanning vertices of $\omega$, i.e. those $v_j \in \text{Vt}(S)$ with $t_j > 0$ in (22). Note that if $\omega \in K \subset S$, where $K$ is a face of the simplex $S$, then

$$\text{SpVt}(\omega; S) = \text{SpVt}(\omega; K).$$

If $U$ is a real vector space, a map $A : V \to U$ is affine if $A(v) = L(v) + C$, where $L : V \to U$ is $\mathbb{R}$-linear and $C \in U$ is fixed. If $S = \{v_0, v_1, \ldots, v_p\} \subset V$ is a simplex, a map $H : S \to U$ is called affine if it is the restriction to $S$ of an affine map $A : \mathbb{R}S \to U$. Here $\mathbb{R}S$ is the vector subspace of $V$ spanned by the $v_i$. In terms of the barycentric expansion such a map satisfies

$$H(\omega) = \sum_{j=0}^{p} t_j H(v_j) \quad (\omega = \sum_{j=0}^{p} t_j v_j, \quad \sum_{j=0}^{p} t_j = 1, \quad t_j \geq 0 \text{ for } 0 \leq j \leq p),$$

and so is determined by the $H(v_j)$. In fact, $H(\omega)$ is determined by the values of $H$ on the spanning vertices of $\omega$. Conversely, if for each vertex $v_i$ of $S$ we choose some $H(v_j) \in U$, then (24) defines a unique affine map $H : S \to U$.

If $S' = \{u_0, u_1, \ldots, u_q\} \subset U$ is a simplex in $U$, a map $T : S \to S'$ is called simplicial if it is an affine map from $S$ to $U$ that takes vertices of $S$ to vertices of $S'$. An injective simplicial map $T$ preserves barycentric coordinates, i.e. if $t_j$ is the barycentric coordinate of $\omega \in S$ corresponding to a vertex $v_j$, then $t_j$ is also the barycentric coordinate of $T(\omega) \in S'$ corresponding to the vertex $T(v_j)$.

3.2. $\Lambda$-complexes. Recall that in 2.1 we defined an ordered complex

$$X = \bigcup_{\alpha \in \mathfrak{I}} X_{\alpha}.$$

A map of complexes $X \to X'$, where $X' = \bigcup_{\beta \in \mathfrak{I}'} X_{\beta}'$, is a map of index sets $\tilde{T} : \mathfrak{I} \to \mathfrak{I}'$ together with a map of point sets $T : X \to X'$ such that $T$ restricted to each $X_{\alpha}$ is a simplicial map to $X_{T(\alpha)}'$. If $\tilde{T}$ and $T$ are bijections, the set-theoretic inverse of $T$ is also a map of complexes, and so the complexes are isomorphic.

**Definition 2.** Suppose $V$ is a $p$-dimensional real vector space, $\Lambda \subset V$ is a full lattice (i.e. a discrete subgroup of $V$ whose $\mathbb{R}$-span is $V$), and $X = \bigcup_{\alpha \in \mathfrak{I}} X_{\alpha} <_{\alpha} \subset V$ is an ordered $p$-complex in $V$. We shall say that $X$ is a $\Lambda$-complex if it satisfies the following five properties.

(i) $X$ is a simplicial complex, i.e. for $\alpha, \beta \in \mathfrak{I}$, $X_{\alpha} \cap X_{\beta}$ is empty or

$$X_{\alpha} \cap X_{\beta} = \{v_1, \ldots, v_\ell\}, \quad \text{where} \quad \{v_1, \ldots, v_\ell\} := \text{Vt}(X_{\alpha}) \cap \text{Vt}(X_{\beta}).$$

In other words, simplices intersect along common faces.

(ii) The orders are compatible, i.e.

$$v <_{\alpha} w \iff v <_{\beta} w \quad (\alpha, \beta \in \mathfrak{I}, v, w \in \text{Vt}(X_{\alpha}) \cap \text{Vt}(X_{\beta})).$$
(iii) The orders are $\Lambda$-invariant, i.e., for $\alpha, \alpha' \in \mathcal{J}$, if $v, w \in \text{Vt}(X_{\alpha})$ and $v + \lambda, w + \lambda \in \text{Vt}(X_{\alpha'})$ for some $\lambda \in \Lambda$, then
\[
v \prec_{\alpha} w \iff v + \lambda \prec_{\alpha'} w + \lambda.
\]
(iv) $X$ is nearly a fundamental domain for $\Lambda$, i.e., the restriction to $X$ of the natural quotient map from $V$ to $V/\Lambda$ is surjective, and it is injective when restricted to the union $\bigcup_{\alpha \in \mathcal{J}} X_{\alpha}$ of the interiors of the $X_{\alpha}$.

(v) The spanning vertices are $\Lambda$-equivariant, i.e.
\[
[x, x' \in X, \lambda \in \Lambda, x' = x + \lambda] \implies \text{SpVt}(x') = \text{SpVt}(x) + \lambda.
\]
Note that if $X$ is simplicial (in the sense of (i) above) and $X'$ is an isomorphic complex, then $X'$ is also simplicial.

Next we state the main result of this section.

**Proposition 3.** Let the $p$-complex $X = \bigcup_{\alpha \in \mathcal{J}} X_{\alpha, \prec_{\alpha}}$ be a $\Lambda$-complex in $V = \mathbb{R}^\Lambda$, let $M_1 < M_2$ be integers, let $\hat{\Lambda} := \Lambda \times (M_2 - M_1)\mathbb{Z}$, and let $\omega : V \to \mathbb{R}$ be a linear function. Then the ordered $(p + 1)$-complex defined in (2.1)
\[
Y(X, \omega, [M_1, M_2]) = \bigcup_{\gamma \in J} Y_{\gamma, \prec_{\gamma}} \subset V \times \mathbb{R},
\]
is a $\hat{\Lambda}$-complex. Furthermore, if $\gamma = (\alpha, v, \ell) \in J$ and we define $\Omega : V \times \mathbb{R} \to \mathbb{R}$ by $\Omega(s, t) := \omega(s) + t$, then for all $\kappa \in Y_{\gamma}$ we have
\[
A(v) + \ell - 1 \leq \Omega(\kappa) \leq A(v) + \ell,
\]
where $A(v)$ is the upper fractional part of $\omega(v)$ defined in (6).

In the next three subsections we prove a series of lemmas leading to a proof in \[3.6\] of the above proposition.

### 3.3. Simplicial decomposition of $X \times [M_1, M_2]$.

**Lemma 4.** Let $I = [0, 1] \subset \mathbb{R}$ be the unit interval, let $S = S_{\prec}$ be an ordered $p$-simplex in some real $p$-dimensional vector space $V$, and write $S = [v_0, v_1, \ldots, v_p]$ as the convex hull of its $p + 1$ vertices, ordered so that $v_0 \prec v_1 \prec \cdots \prec v_p$. For any vertex $v = v_j \in \text{Vt}(S)$, let
\[
S^v = S^v_{\prec} := [v_0 \times 1, v_1 \times 1, \ldots, v_j \times 1, v_j \times 0, v_{j+1} \times 0, \ldots, v_p \times 0] \subset S \times I \subset V \times \mathbb{R}.
\]
Then $S^v$ is an ordered $(p + 1)$-simplex if we define, for $w, w' \in \text{Vt}(S^v)$,
\[
w \prec^v w' \iff [\pi_V(w) \prec \pi_V(w')] \text{ or } [\pi_V(w) = \pi_V(w') \text{ and } \pi_\mathbb{R}(w') < \pi_\mathbb{R}(w)],
\]

---

4 As the complex $X = \bigcup_{\alpha \in \mathcal{J}} X_{\alpha}$ is assumed simplicial, (23) shows that the set $\text{SpVt}(x) = \text{SpVt}(x; X_{\alpha})$ of spanning vertices of $x \in X$ is independent of the simplex $X_{\alpha}$ containing $x$ used to calculate the barycentric expansion of $x$. We will write $\text{SpVt}(x; X)$ when we wish to specify the simplicial complex involved.
where \( \pi_V : V \times \mathbb{R} \to V \) and \( \pi_R : V \times \mathbb{R} \to \mathbb{R} \) are the natural projections. Furthermore, \( S \times I = \bigcup_{v \in V(S)} S_v \), and this is an ordered simplicial \((p+1)\)-complex, i.e. it satisfies (25) and (26).

Proof. It is immediate that \( S_v \) is a \((p+1)\)-simplex and that (30) makes \( \bigcup_v S_v \) into an ordered complex satisfying (26). To see that it is simplicial, i.e. satisfies (25), we will show that it is isomorphic to the standard simplicial decomposition of \( \Delta_p \times I \), where \( \Delta_p \) is the standard \( p \)-simplex. Indeed, let \( e_1, \ldots, e_p \) be the standard basis of \( \mathbb{R}^p \) and set \( E_0 := 0_{\mathbb{R}^p} \in \mathbb{R}^p \), \( E_i := e_i + E_{i-1} \) \((1 \leq i \leq p)\), and let \( A : V \to \mathbb{R}^p \) be the unique affine isomorphism satisfying \( A(v_i) := E_{p-i} \) \((0 \leq i \leq p)\), so that

\[
A(S) = [E_p, E_{p-1}, \ldots, E_0] = \Delta_p = \{ x \in \mathbb{R}^p \mid 1 \geq x_1 \geq x_2 \geq \cdots \geq x_p \geq 0 \}.
\]

Let \( \hat{A} : V \times \mathbb{R} \to \mathbb{R}^p \times \mathbb{R} \) be the affine isomorphism given by \( \hat{A}(v \times y) := A(v) \times y \in \mathbb{R}^p \times \mathbb{R} = \mathbb{R}^{p+1} \). Then \( \hat{A}(S \times I) = \Delta_p \times I \), and

\[
\hat{A}(S(v)) = [E_p \times 1, \ldots, E_{p-j} \times 1, E_{p-j} \times 0, E_{p-j-1} \times 0, \ldots, E_0 \times 0] = \{ x \in \mathbb{R}^{p+1} \mid 1 \geq x_1 \geq \cdots \geq x_{p-j} \geq x_{p-j+1} \geq \cdots \geq x_p \geq 0 \}
\]

(0 \leq j \leq p). This is the standard decomposition of the product \( \Delta_p \times I \), easily seen to be simplicial.

Next we record some simple properties of the above decomposition of \( S \times I \).

(a) The projection \( \pi_V : V \times \mathbb{R} \to V \) maps \( S_v \) onto \( S \), and maps the vertices of \( S_v \) bijectively onto the vertices of \( S \), except for the vertices \( v \times 0 \) and \( v \times 1 \), both of which map to \( v \).

(b) Let \( S_v^- \) and \( S_v^+ \) be the \( p \)-faces of \( S_v \) defined by

\[
S_v^- = S_v^0 := \{ v_0 \times 1, v_1 \times 1, \ldots, v_{j-1} \times 1, v_j \times 0, v_{j+1} \times 0, \ldots, v_p \times 0 \},
\]

\[
S_v^+ = S_v^0 := \{ v_0 \times 1, v_1 \times 1, \ldots, v_{j-1} \times 1, v_j \times 1, v_{j+1} \times 0, \ldots, v_p \times 0 \}.
\]

If \( w \in S \), then \( w \times 0 \) is contained in a proper face of \( S_v \), namely in \( S_v^- := \{ v_0 \times 0, v_1 \times 0, \ldots, v_p \times 0 \} \subset S_v^0 \). Similarly, \( w \times 1 \) is contained in a proper face of \( S_v^+ \), and

\[
S_v^{p+} := \{ v_0 \times 1, v_1 \times 1, \ldots, v_p \times 1 \} = S_v^0 + (0 \times 1) \subset S_v^p,
\]

where \( 0 \times 1 \in V \) is the origin in \( V \).

Lemma 5. Suppose \( X = \bigcup_{\alpha \in \mathcal{J}} X_{\alpha, \prec} \) is an ordered simplicial \( p \)-complex. Then

\[
X \times I = \bigcup_{\alpha \in \mathcal{J}} \bigcup_{v \in Vt(X_\alpha)} X_{\alpha, \prec}^v
\]

is an ordered simplicial \((p+1)\)-complex. Here \( I \) is the closed interval \([0,1]\) and \( X_{\alpha, \prec}^v \) was defined in Lemma 4, taking \( S_< := X_{\alpha, \prec} \).

Proof. The equality of sets in (33) is clear from Lemma 4. By the same lemma, it is easy to see that (33) is an ordered \((p+1)\)-complex. We now show that the decomposition is simplicial. Suppose \( \delta = \omega \times y \in X_\alpha^v \cap X_\beta^v \). We will show that the spanning vertices of \( \delta \) satisfy \( SpVt(\delta; X_\alpha^v) = SpVt(\delta; X_\beta^v) \). This suffices as it shows that \( \delta \) lies in the convex hull of \( Vt(X_\alpha^v) \cap Vt(X_\beta^v) \). Let \( L := X_\alpha \cap X_\beta \), a non-empty simplex as \( \omega \in L \), and a common face of the simplices \( X_\alpha \) and \( X_\beta \). Then \( \delta \in L \times I \), so by Lemma 4 \( \delta \in L^\mu \) for some vertex \( \mu \in Vt(L) = Vt(X_\alpha) \cap Vt(X_\beta) \). But \( L^\mu \) is
a face of \(X^\mu\) and of \(X^\nu\), as follows immediately from the construction of Lemma 4. Therefore \(\delta \in X^\mu \cap X^\nu\) and \(\delta \in X^\mu \cap X^\nu\). Since \(X\alpha \times I = \bigcup_{p \in Vt(X\alpha)} X^\alpha\) is simplicial by Lemma 4, we have

\[
\text{SpVt}(\delta; X^\mu) = \text{SpVt}(\delta; X^\nu) = \text{SpVt}(\delta; L^\mu) = \text{SpVt}(\delta; X^\nu) = \text{SpVt}(\delta; X^\nu).
\]

Next we use translations in the last coordinate to extend the decomposition of Lemma 4 from \(X \times I\) to \(X \times [M_1, M_2]\). Given an ordered \(p\)-complex \(X = \bigcup_{\alpha \in \mathcal{I}} X\alpha \subset V\), define the ordered \((p+1)\)-simplex \(X^\gamma = X^\gamma_{\alpha,\gamma}\) by

\[
X^\gamma := X^\alpha + (0_V \times \ell) \quad (\gamma = (\alpha, v, \ell), \alpha \in \mathcal{I}, v \in Vt(X\alpha), \ell \in \mathbb{Z}),
\]

where \(\prec\) is defined by (30). Thus, for \(w, w' \in Vt(X^\gamma)\),

\[
w \prec w' \iff [\pi_V(w) \prec_{\alpha} \pi_V(w')] \text{ or } \pi_V(w) = \pi_V(w') \text{ and } \pi_\mathbb{R}(w) < \pi_\mathbb{R}(w').
\]

Note that when \(\gamma \in \mathcal{J}\) in (34), then \(M_1 \leq \ell < M_2\).

**Lemma 6.** Let \(M_1 < M_2\) be integers, suppose \(X = \bigcup_{\alpha \in \mathcal{I}} X\alpha_{\prec,\alpha}\) is an ordered simplicial \(p\)-complex, and let \(X^\gamma = X^\gamma_{\alpha,\gamma}\) be as in (34) and (35). Then

\[
X \times [M_1, M_2] = \bigcup_{\gamma \in \mathcal{J}} X^\gamma = \bigcup_{\gamma \in \mathcal{J}} X^\gamma_{\alpha,\gamma}
\]

is an ordered simplicial \((p+1)\)-complex.

**Proof.** As in the proof of Lemma 4, applying an affine isomorphism it is easy to see that

\[
X\alpha \times [M_1, M_2] = \bigcup_{M_1 \leq \ell < M_2} \left( (X^\alpha_{\alpha} + (0_V \times \ell)) \right)
\]

is an ordered simplicial \((p+1)\)-complex. The rest follows the proof of Lemma 4. \(\square\)

We can take \(M_1 \rightarrow -\infty\) and \(M_2 \rightarrow +\infty\) in (36), as we record next.

**Corollary 7.** Let \(X\) be as in Lemma 6 and let

\[
J_\infty := \{ (\alpha, v, \ell) \mid \alpha \in \mathcal{I}, v \in Vt(X\alpha), \ell \in \mathbb{Z} \}.
\]

Then \(X \times \mathbb{R} = \bigcup_{\gamma \in J_\infty} X^\gamma\) is an ordered simplicial \((p+1)\)-complex.

**Lemma 8.** Let \(X, M_1\) and \(M_2\) be as in Lemma 4. Suppose \(\rho \in X \times [M_1, M_2]\) and \(\pi_\mathbb{V}(\rho) \in X\alpha\). Then there is some \(v \in \text{SpVt}(\pi_\mathbb{V}(\rho)) \subset Vt(X\alpha)\) and an integer \(\ell\) satisfying \(M_1 \leq \ell < M_2\) such that \(\rho \in X^\gamma\), where \(\gamma = (\alpha, v, \ell)\).

**Proof.** Lemma 6 shows that any \(\rho \in X \times [M_1, M_2]\) belongs to some simplex \(X^\gamma\) with \(\gamma = (\alpha, v, \ell)\). Our next result shows that \(v\) can be chosen to be a spanning vertex of the projection \(\pi_\mathbb{V}(\rho) \in X\).

**Lemma 9.** Let \(X, M_1\) and \(M_2\) be as in Lemma 4. Suppose \(\rho \in X \times [M_1, M_2]\) and \(\pi_\mathbb{V}(\rho) \in X\alpha\). Then there is some \(v \in \text{SpVt}(\pi_\mathbb{V}(\rho)) \subset Vt(X\alpha)\) and an integer \(\ell\) satisfying \(M_1 \leq \ell < M_2\) such that \(\rho \in X^\gamma\), where \(\gamma = (\alpha, v, \ell)\).

**Proof.** Lemma 6 shows that \(\rho \in X^\Delta\) for some \(\Delta = (\alpha, w, \ell) \in J\). If \(w \times \ell\) or \(w \times (\ell + 1)\) is a spanning vertex of \(\rho\) (with respect to \(X^\Delta\)), then \(w = \pi_\mathbb{V}(w \times \ell) = \pi_\mathbb{V}(w \times (\ell + 1))\) is a spanning vertex of \(\pi_\mathbb{V}(\rho)\), and we may pick \(v := w\). Otherwise,

\[
\text{SpVt}(\rho) = \{ v_1 \times (\ell + 1), \ldots, v_t \times (\ell + 1), w_1 \times \ell, \ldots, w_r \times \ell \},
\]
where, by definition (36) of $X$, the $v_i$ and $w_j$ are vertices of $X$ satisfying

$$v_1 <_\alpha v_2 <_\alpha \cdots <_\alpha v_t <_\alpha w <_\alpha w_1 <_\alpha w_2 <_\alpha \cdots <_\alpha w_r.$$  

Applying $\pi_V$ to (37) we obtain

$$\text{SpVt}(\pi_V(\rho)) = \{v_1, \ldots, v_t, w_1, \ldots, w_r\}.$$  

If $t > 0$, let $v := v_t$. Otherwise, let $v := w_1$. Then, from (37), (39) and (29), $\text{SpVt}(\rho) \subset \text{Vt}(X)$. Hence $\rho \in X$ and $v \in \text{SpVt}(\pi_V(\rho))$.  

3.4. The complex $Y$. Throughout this subsection we assume, as in Proposition 3 that $M_1 < M_2$ are integers and that $X = \bigcup_{\alpha \in J} X_{\alpha, <_\alpha} \subset V$ is a simplicial $p$-complex contained in some vector space $V$, with compatible orders $<_\alpha$ in the sense of (20). So far in this section we have made no use of the linear function $\omega : V \to \mathbb{R}$ in Proposition 3. Now we will use $\omega$ to make two changes in the construction of the complexes $X$ in Lemma 3. First we will replace the given order $<_\alpha$ on the vertices of $X_{\alpha}$ by a new order $<_\alpha^A$ which depends on $\omega$. Then, using the piecewise affine map $T$ defined below, we will make a change in the last coordinate of elements of $X \times \mathbb{R}$ to obtain the simplices $Y_{\gamma}$ in Proposition 3.

Recall that for $u, u' \in \text{Vt}(X_{\alpha})$ we defined in (37)

$$u <_\alpha^A u' \iff \left[\lfloor A(u) < A(u') \rfloor \right] \text{ or } \left[\lfloor A(u) = A(u') \text{ and } u <_\alpha u' \right],$$

where $A$ is the upper fractional part of $\omega$. A trivial verification shows that if the orders $<_\alpha$ are compatible, then so are the orders $<_\alpha^A$.

Applying Lemma 3 to the ordered simplicial complex $X := \bigcup_{\alpha \in J} X_{\alpha, <_\alpha^A}$, we obtain the simplicial complex

$$X \times [M_1, M_2] = \bigcup_{\gamma \in J} X_{\gamma} =: X^A,$$

where we have called the new simplices $X_{\gamma}^A$ (instead of $X_{\gamma}$) to clarify that the original order $<_\alpha$ on the vertices of $X_{\alpha}$ has been replaced by $<_\alpha^A$. We have also denoted by $X^A$ the corresponding simplicial decomposition of $X \times [M_1, M_2]$. By Corollary 7 we also get a simplicial complex

$$X \times \mathbb{R} = \bigcup_{\gamma \in J_{\infty}} X_{\gamma} =: X^A_{\infty}.$$  

For $\gamma = (\alpha, v, \ell) \in J_{\infty}$, i.e. $\alpha \in J$, $v \in \text{Vt}(X_{\alpha})$ and $\ell \in \mathbb{Z}$, let

$$T_{\gamma} := V \times \mathbb{R} \to V \times \mathbb{R}$$

be the unique affine function which on any vertex $\sigma \in \text{Vt}(X^A_{\gamma})$ satisfies

$$T_{\gamma}(\sigma) := \sigma + \left(0 \times (A(\pi_V(\sigma)) - \omega(\pi_V(\sigma)) - 1)\right) \quad (\sigma \in \text{Vt}(X^A_{\gamma})), $$

where $\pi_V : V \times \mathbb{R} \to V$ is the projection to the first component and $0_V$ is the origin in $V$. Actually, $T_{\gamma}(\sigma) \in X \times \mathbb{Z}$ since $\sigma \in X \times \mathbb{Z}$ by (29) and (34), while $A(v) - \omega(v) \in \mathbb{Z}$ by (19). Since $T_{\gamma}(\sigma)$ depends only on $\sigma$ (and not on the simplex $X^A_{\gamma}$).

---

5 We do not consider $X^A$ as an ordered complex since this is not the complex $Y$ appearing in Proposition 3. To get $Y$ we will still need to apply the map $T$ studied in Lemma 3 below.
to which it belongs) and $X^{\mathcal{A}}$ is a simplicial complex, there is a unique piecewise affine function

\begin{equation}
T : X \times \mathbb{R} \to X \times \mathbb{R}, \quad T(\rho) = T_\gamma(\rho) := \sum_{\sigma \in \operatorname{Vt}(X^{\mathcal{A}})} c_\sigma T_\gamma(\sigma) \quad (\rho \in X^{\mathcal{A}}),
\end{equation}

where

\begin{equation}
\rho = \sum_{\sigma \in \operatorname{Vt}(X^{\mathcal{A}})} c_\sigma \sigma \quad \left( \sum_{\sigma \in \operatorname{Vt}(X^{\mathcal{A}})} c_\sigma = 1, \quad c_\sigma \geq 0 \right).
\end{equation}

Note that $T(\rho) = \rho$ if $\omega$ vanishes identically.

**Lemma 9.** Suppose $X = \bigcup_{n \in \mathbb{N}} X_{\alpha_n} \subset V$ is a simplicial complex in some vector space $V$, with compatible orders $\prec_n$. Then the piecewise affine function $T : X \times \mathbb{R} \to X \times \mathbb{R}$ defined in (11) is a bijection. It satisfies the identities

\begin{equation}
\pi_V \circ T = \pi_V, \quad T((s \times t) + (0_V \times t')) = T(s \times t) + (0_V \times t') \quad (s \in X, \ t, t' \in \mathbb{R}),
\end{equation}

and

\begin{equation}
T(s \times t) = s \times (r_s + t) \quad (s \in X, \ t \in \mathbb{R}, \ s \times r_s := T(s \times 0)).
\end{equation}

**Proof.** The last identity implies the first two, and hence that $T$ is a bijection. To prove (14), let $\rho = s \times t \in X^{\mathcal{A}}$, where $\gamma = (\alpha, v, \ell)$. From (10), (11) and (12), we get

\begin{equation}
T(\rho) = \sum_{\sigma \in \operatorname{Vt}(X^{\mathcal{A}})} c_\sigma \left( \sigma + (0_V \times (A(\pi_V(\sigma)) - \omega(\pi_V(\sigma)) - 1)) \right)
\end{equation}

\begin{equation}
= \rho - (0_V \times \omega(\pi_V(\rho))) + (0_V \times q),
\end{equation}

where $q = q(s \times t) := -1 + \sum_{\sigma} c_\sigma A(\pi_V(\sigma))$.

Now, $\pi_V$ restricted to $\operatorname{Vt}(X^{\mathcal{A}})$ is a bijection onto $\operatorname{Vt}(X_\alpha)$, except for the two vertices $v \times \ell$ and $v \times (\ell + 1)$, both of which map to $v$ (see (14) and (a) after the proof of Lemma 4). From (12) we have

\begin{equation}
s = \pi_V(s \times t) = \sum_{\sigma \in \operatorname{Vt}(X^{\mathcal{A}})} c_\sigma \pi_V(\sigma) = \sum_{\delta \in \operatorname{Vt}(X_\alpha)} d_\delta \delta,
\end{equation}

where in the last equation we have simply written the barycentric expansion of $s$ with respect to $X_\alpha$ (see the remarks after (22)). Since barycentric coordinates with respect to a simplex are unique, we have $c_{v \times \ell} + c_{v \times (\ell + 1)} = d_v$ and $c_\sigma = d_{\pi_V(\sigma)}$ for $\pi_V(\sigma) \neq v$. Hence

\begin{equation}
q(s \times t) := -1 + \sum_{\sigma} c_\sigma A(\pi_V(\sigma)) = -1 + \sum_{\delta \in \operatorname{Vt}(X_\alpha)} d_\delta A(\delta).
\end{equation}

But the $d_\delta$ are uniquely determined by $s$, so $q(s \times t) = q(s \times 0)$. Now (14) follows from (15). \qed

By the lemma just proved, the affine function $T_\gamma : V \times \mathbb{R} \to V \times \mathbb{R}$ is injective when restricted to a non-empty open subset of $V \times \mathbb{R}$, namely on the interior of any $X^{\mathcal{A}}$. Hence $T_\gamma$ is an affine bijection. Thus

\begin{equation}
T(X^{\mathcal{A}}) = T_\gamma(X^{\mathcal{A}}) \subset X \times \mathbb{R}
\end{equation}

is a $(p + 1)$-simplex and
There are two vertices with \( \delta \) we have \( \kappa \)
first the case By (40), \( \kappa \)
Since \( \Omega \) is linear, it suffices to prove (c) for all vertices
have \( \Omega \)
Applying definition (40) of \( T \)
(46)
\[
X^A = X \times [M_1, M_2] = \bigcup_{\gamma \in J} T(X^{\gamma_A}).
\]
Since, as remarked before \( \text{[59]} \), \( X^A \) is a simplicial complex, so is \( T(X^A) \).
We can now prove part of Proposition \( \text{[3]} \)

Lemma 10. With the hypotheses and notation of Proposition \( \text{[3]} \) the following hold.
(a) \( Y_{\gamma} = T(X^{\gamma_A}), \) \( Vt(Y_{\gamma}) = T(Vt(X^{\gamma_A})) \) (\( \gamma \in J \)), and so by \( \text{[16]} \), \( Y = T(X \times [M_1, M_2]) \).
(b) \( Y = Y(X, \omega, [M_1, M_2]) = \bigcup_{\gamma \in J} Y_{\gamma, <\gamma} \) is an ordered simplicial \((p + 1)\)-complex
and the orders \( \prec_{\gamma} \) are compatible.
(c) Define \( \Omega : V \times \mathbb{R} \to \mathbb{R} \) by \( \Omega(s \times t) := \omega(s) + t \).
Then for all \( \kappa \in Y_{\gamma}, \)
\[
A(v) + \ell - 1 \leq \Omega(\kappa) \leq A(v) + \ell \quad (\gamma = (\alpha, v, \ell) \in J).
\]

Proof. The second and third equations in (a) follow directly from the first one and Lemma \( \text{[9]} \) To prove the first equation in (a), we start with the case \( \gamma = (\alpha, v, 0) \) with \( \alpha \in \mathcal{J} \) and \( v \in Vt(X_{\alpha}) \). Unraveling definition \( \text{[59]} \), \( X^{\gamma_A} = S^n \), where we have applied Lemma \( \text{[1]} \) to \( S_\prec := X_{\alpha, <\alpha} \).
If we order the vertices of \( X_{\alpha} \) as \( v_0 \prec_{\alpha} v_1 \prec_{\alpha} \ldots \prec_{\alpha} v_p \), then by \( \text{[29]} \) the vertices of \( X^{\gamma_A} \) are
\[
\{v_0 \times 1, v_1 \times 1, \ldots, v_j \times 1, v_j \times 0, v_{j+1} \times 0, \ldots, v_p \times 0 \} \quad (v_j = v).
\]
Applying definition \( \text{[10]} \) of \( T_{\gamma} \), the vertices of \( T(X^{\gamma_A}) = T_{\gamma}(X^{\gamma_A}) \) are
\[
\{v_0 \times (A(v_0) - \omega(v_0)), \ldots, v_j \times (A(v_j) - \omega(v_j)), v_j \times (A(v_j) - \omega(v_j) - 1),
\]
\[
v_{j+1} \times (A(v_{j+1}) - \omega(v_{j+1}) - 1), \ldots, v_p \times (A(v_p) - \omega(v_p) - 1) \}.
\]
Comparing this with the definition \( \text{[8]} \) of the vertices of \( Y_{\gamma} \), we find that we have proved (a) for \( \gamma = (\alpha, v, 0) \). This implies (a) for any \( \gamma = (\alpha, v, \ell) \) since \( Y_{(\alpha, v, \ell)} = Y_{(\alpha, v, 0)} + (0v \times \ell) \) by \( \text{[8]} \), while by \( \text{[34]} \) and \( \text{[53]} \)
\[
X^{(\alpha, v, \ell)A} = X^{(\alpha, v, 0)A} + (0v \times \ell), \quad T((s \times t) + (0v \times \ell)) = T((s \times t)) + (0v \times \ell).
\]
As we remarked just before stating Lemma \( \text{[10]} \) the \((p + 1)\)-complex \( \bigcup_{\gamma \in J} T(X^{\gamma_A}) \) is simplicial. By (a), \( T([X \times [M_1, M_2]]) = \bigcup_{\gamma \in J} Y_{\gamma} =: Y \) is simplicial. This proves (b) since the assumed compatibility of the \( \prec_{\alpha} \) immediately implies that of the \( \prec_{\gamma} \) defined in \( \text{[9]} \).

We now prove (c). Just as in the proof of (a), it suffices to take \( \gamma = (\alpha, v, 0) \). Since \( \Omega \) is linear, it suffices to prove (c) for all vertices \( \kappa \in Vt(Y_{\gamma}) \). Since \( \ell = 0 \), by (a) we have \( \kappa = T(\delta \times t) \), where \( \delta \in Vt(X_{\alpha}) \), \( t = 1 \) if \( \delta \prec_{\alpha} v \) and \( t = 0 \) if \( v \prec_{\alpha} \delta \).
By \( \text{[10]} \),
\[
(47) \quad \Omega(\kappa) = \Omega(\delta \times t) + \Omega(0v \times (A(\delta) - \omega(\delta) - 1)) = t + A(\delta) - 1.
\]
There are two vertices with \( \delta = v \), namely \( T(v \times 0) \) and \( T(v \times 1) \). From \( \text{[47]} \) we have \( \Omega(T(v \times 0)) = A(v) - 1 \) and \( \Omega(T(v \times 1)) = A(v) \), proving (c) for the vertices \( T(v \times 0) \) and \( T(v \times 1) \).
We may therefore restrict to \( \kappa = T(\delta \times t) \in Vt(Y_{\gamma}) \) with \( \delta \neq v \). We consider first the case \( A(\delta) = A(v) \). Then \( \text{[47]} \) gives \( \Omega(\kappa) = A(v) - 1 \) if \( t = 0 \), while if \( t = 1 \).
we have $\Omega(\kappa) = A(v)$. Hence (c) holds if $A(\delta) = A(v)$. If $A(\delta) \neq A(v)$, then by definition (38) of the order $\prec_A$, we have $t = 1$ if and only if $A(\delta) < A(v)$. If $t = 1$, then (c) follows from

$$A(v) - 1 \leq 0 < A(\delta) = \Omega(\kappa) < A(v),$$

where we again used (47) for the equality. If $t = 0$, so $A(\delta) > A(v)$, then

$$A(v) > 0 \geq A(\delta) - 1 = \Omega(\kappa) > A(v) - 1,$$

which proves (c) in the last remaining case.

3.5. $\Lambda$-invariance. Although we have assumed in Proposition 3 that the orders $\prec_\alpha$ on $V_t(X_\alpha)$ are invariant with respect to a lattice $\Lambda$, the new orders $\prec_A$ on $V_t(X_\alpha)$ in general are not $\Lambda$-invariant. We shall prove now that this deviation is determined by

$$(51) \quad \Delta_v,\lambda := A(v) + A(\lambda) - A(v + \lambda) = \begin{cases} 0 & \text{if } A(v) + A(\lambda) \leq 1, \\ 1 & \text{if } A(v) + A(\lambda) > 1, \end{cases}$$

where the last equality used (8) and the linearity of $\omega$.

**Lemma 11.** Let $\Lambda \subset V$ be a lattice for which $X = \bigcup_{\alpha \in J} X_\alpha,\prec_\alpha$ has $\Lambda$-invariant orders $\prec_\alpha$ (see (27)), let $\omega : V \to \mathbb{R}$ be a linear function, define $\prec_A$ and $\Delta$ as in (38) and (39). Suppose $v$ and $w$ are vertices of $X_\alpha$ and, for some $\lambda \in \Lambda$, $v + \lambda$ and $w + \lambda$ are vertices of $X_{\alpha'}$ ($\alpha, \alpha' \in J$).

Then, translation preserves order if $\Delta_v,\lambda = \Delta_{v,\lambda}$, i.e.

$$(49) \quad v \prec_A w \iff v + \lambda \prec_A w + \lambda \quad (\Delta_v,\lambda = \Delta_{v,\lambda}),$$

while it reverses order if $\Delta_v,\lambda \neq \Delta_{v,\lambda}$, i.e.

$$(50) \quad v \prec_A w \iff w + \lambda \prec_A v + \lambda \quad (\Delta_v,\lambda \neq \Delta_{v,\lambda}).$$

Moreover,

$$(51) \quad A(v) = A(w) \iff A(v + \lambda) = A(w + \lambda),$$

and

$$(52) \quad A(v) = A(w) \implies \Delta_v,\lambda = \Delta_{v,\lambda}.$$

**Proof.** From (48) we obtain

$$(53) \quad (A(v + \lambda) - A(w + \lambda)) - (A(v) - A(w)) = \Delta_{w,\lambda} - \Delta_v,\lambda = -1, 0, \text{ or } 1.$$

As $A$ takes values in $(0,1]$, (51) and (52) follow.

We now turn to the first two claims in the lemma. If $A(v) = A(w)$, then $\Delta_{w,\lambda} = \Delta_v,\lambda$ and the orders $\prec_A$ and $\prec_A'$ in (49) reduce to $\prec_\alpha$ and $\prec_{\alpha'}$, respectively. In this case (49) follows from the assumed $\Lambda$-invariance of the order (27). We may therefore suppose $A(v) \neq A(w)$. Then $A(v + \lambda) \neq A(w + \lambda)$ and the orders $\prec_A$ and $\prec_A'$ in (49) and (50) reduce to the usual order of $A$-values (see (38)). If $\Delta_{w,\lambda} = \Delta_v,\lambda$, then (53) shows that $A(v) - A(w) = A(v + \lambda) - A(w + \lambda)$, so (48) follows. If $\Delta_{w,\lambda} \neq \Delta_v,\lambda$, then

$$\left|(A(v + \lambda) - A(w + \lambda)) - (A(v) - A(w))\right| = 1.$$

But this is the distance between two real numbers in the open interval $(-1,1)$, which must therefore have opposite signs. This proves (50). \qed
Lemma 12. Let $\Delta \subset V$ be a full lattice in a vector space $V$, let $X = \bigcup_{\alpha \in \mathcal{I}} X_{\alpha} \subset V$ be a $\Delta$-complex (see Definition[2]), $\omega : V \to \mathbb{R}$ a linear function, $Y = \bigcup_{j \in J} Y_{j,\prec,\kappa} \subset V \times \mathbb{R}$ as in (53) [2] and $\pi_V : V \times \mathbb{R} \to V$ the projection. Assume that for some $\alpha \in \mathcal{I}$, $v, \lambda \in \Delta$ we have $(v + \lambda) \in Vt(X_{\alpha'})$ for some $\alpha' \in \mathcal{I}$. Suppose also that $\kappa \in \operatorname{Vt}(Y_{\alpha,v,t})$ and $(\pi_V(\kappa) + \lambda) \in \operatorname{Vt}(X_{\alpha'})$. Then $(\kappa + \lambda) \in \operatorname{Vt}(Y_{\alpha',v+\lambda,t})$, where

$$\hat{\lambda} = \lambda \times j \in \Delta \times \mathbb{Z}, \quad j := A(\lambda) - \omega(\lambda) - \Delta(v, \lambda),$$

$A$ being as in (3) and $\Delta$ as in (48).

Note that $\hat{\lambda}$ and $\gamma' := (\alpha', v + \lambda, \ell)$ depend on $\lambda$ and on $\gamma := (\alpha, v, \ell)$, but not on $\kappa \in \operatorname{Vt}(Y_{\gamma})$.

Proof. That $j \in \mathbb{Z}$ is immediate from (49) and (48). Now, $\kappa \in \operatorname{Vt}(Y_{\gamma}) = T(\operatorname{Vt}(X_{\gamma',A})))$, by Lemma 11. Thus,

$$\kappa = T(w \times t), \quad w \times t \in \operatorname{Vt}(X_{\gamma',A}), \quad t \in \{\ell, \ell + 1\}, \quad w = \pi_V(\kappa) \in \operatorname{Vt}(X_{\alpha}).$$

By (40),

$$\kappa = T(w \times t) = w \times t + 0_V \times (A(w) - \omega(w) + 1).$$

By assumption, both $v + \lambda$ and $w + \lambda$ are vertices of $X_{\alpha'}$. Thus there exists a vertex

$$\rho \in \operatorname{Vt}(X_{\gamma',A}), \quad \rho = (w + \lambda) \times t', \quad t' \in \{\ell + 1, \ell\}, \quad \gamma' := (\alpha', v + \lambda, \ell).$$

Notice that for $w \neq v$, the value of $t'$ in (56) is determined by $w + \lambda$, but for $w = v$ there are vertices $\rho = (w + \lambda) \times t' \in \operatorname{Vt}(X_{\gamma',A})$ for both values of $t'$. We now calculate

$$T(\rho) = \rho + 0_V \times (A(w + \lambda) - \omega(w + \lambda) - 1) \quad \text{[by (40) and (50)]}$$

$$= (w + \lambda) \times t' + 0_V \times (A(w) + A(\lambda) - \Delta(w, \lambda) - \omega(w) - \omega(\lambda) - 1) \quad \text{[by (48)]}$$

$$= w \times t + 0_V \times (A(w) - \omega(w) - 1) + \lambda \times (A(\lambda) - \omega(\lambda) - \Delta(v, \lambda))$$

$$+ 0_V \times (\Delta(v, \lambda) - \Delta(w, \lambda) + t' - t) \quad [t \text{ as in (55)}]$$

$$= \kappa + \hat{\lambda} + 0_V \times (\Delta(v, \lambda) - \Delta(w, \lambda) + t' - t) \quad \text{[by (54) and (55)].}$$

Since $T(\rho) \in \operatorname{Vt}(Y_{\gamma'})$, Lemma 12 will be proved once we show

$$\Delta(v, \lambda) - \Delta(w, \lambda) + t' - t = 0.$$ (57)

We will do this by checking various cases, bearing in mind that $\Delta = 0$ or $1$ and $t, t' = \ell$ or $\ell + 1$.

If $w = v$, both $(w + \lambda) \times \ell$ and $(w + \lambda) \times (\ell + 1)$ are vertices of $X_{\gamma',A}$. Hence we can pick the vertex $\rho$ so that $t' = t$, making (57) hold trivially. We may therefore assume $w \neq v$, which makes $t$ and $t'$ uniquely determined by $v_{A}$ and $\gamma'_{A}$. Namely, $t = \ell + 1$ is equivalent to $w \sim_{A} v$ (see Lemma 4). Otherwise, $t = \ell$. Similarly, $t' = \ell + 1$ if and only if $w + \lambda \sim_{A} v + \lambda$.

If $\Delta(v, \lambda) = \Delta(w, \lambda)$, Lemma 11 shows $t = t'$, proving (57) in this case. We may therefore assume $\Delta(v, \lambda) \neq \Delta(w, \lambda)$. Thus, again by Lemma 11 $t \neq t'$, $A(v) \neq A(w)$ and $A(v + \lambda) \neq A(w + \lambda)$.

We consider first the case $t = \ell$. Then $v \sim_{A} w$, so $A(w) > A(v)$ by definition (48) of $\sim_{A}$. Also, $t' \neq t$, so $t' = \ell + 1$. We claim $\Delta(w, \lambda) = 1$. Indeed, otherwise $\Delta(w, \lambda) = 0$ and so $\Delta(v, \lambda) = 1$. Therefore, by (48), $A(v) + A(\lambda) > 1$, whence...
\( A(w) + A(\lambda) > 1 \). Then, again by (48), \( \Delta(w, \lambda) = 1 \), a contradiction. Hence, \( \Delta(w, \lambda) = 1 \) and \( \Delta(v, \lambda) = 0 \), from which (57) follows.

Lastly, if \( t = \ell + 1 \), then \( A(w) < A(v) \) and \( t' = \ell \). We claim \( \Delta(v, \lambda) = 1 \). Otherwise \( \Delta(v, \lambda) = 0 \) and \( \Delta(w, \lambda) = 1 \). By (48), \( A(v) + A(\lambda) \leq 1 \). Hence \( A(w) + A(\lambda) < 1 \), proving \( \Delta(w, \lambda) = 0 \), a contradiction. Thus, \( \Delta(v, \lambda) = 1 \), \( \Delta(w, \lambda) = 0 \), and (57) follows. \( \square \)

3.6. Proof of Proposition 53 We need to show that \( Y = \bigcup_{\gamma \in J} Y_{\gamma, <_\gamma} \subset V \times \mathbb{R} \) is an ordered \((p + 1)\)-complex satisfying inequality (28), and properties (i) to (v) in Definition 2 with respect to the lattice \( \hat{\Lambda} := \Lambda \times (M_2 - M_1)\mathbb{Z} \).

Parts (b) and (c) of Lemma 10 show that \( Y \) is an ordered simplicial \((p+1)\)-complex with compatible orders and satisfies inequality (28). We must still prove that \( Y \) has properties (iii) to (v).

We now prove (iii), i.e., if \( \kappa, \delta \in V(\gamma) \) and \( \kappa + \hat{\lambda}, \delta + \hat{\lambda} \in V(\gamma') \) for some \( \hat{\lambda} \in \hat{\Lambda} \), \( \gamma = (\alpha, v, \ell) \), \( \gamma' = (\alpha', v', \ell') \in J \), then we must show

\[
\kappa \prec_{\gamma} \delta \iff \kappa + \hat{\lambda} \prec_{\gamma'} \delta + \hat{\lambda}.
\]

By (49), \( \pi_\gamma \circ T = \pi_\Lambda \), so \( \pi_\gamma \) maps \( V(\gamma) \) to \( V(\gamma') \). Hence (58) is again clear and we have proved (iii).

We now turn to the proof of (iv) in Definition 2, i.e., that \( \Lambda \) is nearly a fundamental domain for \( \hat{\Lambda} \subset V \times \mathbb{R} \). By assumption, \( X \) surjects onto \( V/\Lambda \). Recall from (44) that \( T(x \times s) = x \times (r_x + s) \), where \( r_x \in \mathbb{R} \) is independent of \( s \in \mathbb{R} \). Thus, \( Y = T(X \times [M_1, M_2]) \) surjects onto \( (V \times \mathbb{R})/\hat{\Lambda} \).

To complete the proof of (iv), we show that the union of interiors \( \bigcup_{\gamma \in J} Y'_{\gamma} \) injects into \( (V \times \mathbb{R})/\hat{\Lambda} \). Suppose \( \rho = T(s \times t) \in Y'_{\gamma} \) and \( \rho' = T(s' \times t') \in Y'_{\gamma'} \) map to the same point in \( (V \times \mathbb{R})/\hat{\Lambda} \), for some \( \gamma = (\alpha, v, \ell), \gamma' = (\alpha', v', \ell') \in J \). Since \( \rho \) is in the interior of \( Y_{\gamma} = T(X^{\gamma, A}) \) and \( \pi_\gamma(Y_{\gamma}) = X_{\alpha} \), it follows that \( s = \pi_\gamma(\rho) \in X_{\alpha} \).

Similarly, \( s' \in X_{\alpha'} \). But we are assuming the congruence

\[
(s, r_s + t) = T(s \times t) \equiv T(s' \times t') = s' \times (r_{s'} + t') \pmod{\Lambda \times (M_2 - M_1)\mathbb{Z}},
\]

so \( s \equiv s' \pmod{\Lambda} \). By assumption, \( X = \bigcup_{\alpha} X_{\alpha} \) injects into \( V/\Lambda \). Thus, \( s = s' \). Then

\[
s \times (r_s + t) = T(s \times t) \equiv T(s' \times t') = s \times (r_{s'} + t') \pmod{\hat{\Lambda}},
\]

showing \( t = t' \in (M_2 - M_1)\mathbb{Z} \). It \( t = t' \), then \( t = M_1 \) or \( M_2 \) as \( t, t' \in [M_1, M_2] \).

However, \( t \in \mathbb{Z} \) means that \( s \times t \) lies in a proper face of some \( X^{\gamma', A} \) (see remark
To this end, suppose \( \rho \in \Lambda \) is simplicial complex, this contradicts \( \rho \in \hat{Y}_\gamma \), proving \( (iv) \).

We now turn to the proof of \( (v) \), i.e. the \( \hat{\Lambda} \)-equivariance of the spanning vertices. To this end, suppose

\[
y, y' \in Y = T(X \times [M_1, M_2]), \quad y' = y + \lambda, \quad \hat{\lambda} = \lambda \times j \in \hat{\Lambda}.
\]

We must show that their spanning vertices satisfy

\[
\text{SpVt}(y'; Y) = \lambda + \text{SpVt}(y; Y),
\]

where for clarity we have written \( \text{SpVt}(y; Y) \) to indicate that the spanning vertices are calculated with respect to \( Y \), i.e. with respect to any simplex \( Y_\gamma \subset Y \) containing \( y \). We claim that it suffices to prove

\[
k \in \text{SpVt}(y; Y) \implies k + \lambda \in \text{Vt}(Y_\gamma)
\]

for some \( \gamma \in J \) independent of \( k \). Indeed, the barycentric expansion

\[
y = \sum_{\kappa} c_\kappa k \quad \text{for some } c_\kappa > 0
\]

implies \( y' = y + \lambda = \sum_{\kappa} c_\kappa (k + \lambda) \), proving \( (vi) \) since \( k + \lambda \in \text{Vt}(Y_\gamma) \) by \( (vii) \).

We now prove \( (vi) \). By \( (viii) \) and \( (vii) \),

\[
x' = x + \lambda \in X, \quad x := \pi_V(y) \in X, \quad x' := \pi_V(y') \in X, \quad \lambda := \pi_V(\lambda) \in \Lambda.
\]

Since \( X = \bigcup_{\beta \in J} X_\beta \) is by assumption a \( \Lambda \)-complex,

\[
\text{SpVt}(x'; X) = \lambda + \text{SpVt}(x; X).
\]

As \( y \in Y = T(X \times [M_1, M_2]), \) we have \( y = T(\rho) \in Y_\gamma \) for some \( \gamma = (\alpha, v, \ell) \in J \) and \( \rho \in X^{\gamma \cdot \Lambda} \). Therefore \( \text{SpVt}(y) \subset \text{Vt}(Y_\gamma) \). Similarly, \( y' \in Y_\gamma \) for some \( \gamma' = (\alpha', v', \ell') \in J \). By Lemma 8 and \( (vii) \), we can assume \( v \in \text{SpVt}(x) \subset \text{Vt}(X_\alpha) \).

Let \( k \in \text{SpVt}(y; Y) \subset \text{Vt}(Y_\gamma) \). Then \( \pi_V(k) \in \text{SpVt}(x) \subset \text{Vt}(X_\alpha) \). By \( (viii) \), \( v + \lambda \in \text{Vt}(X_\alpha) \) and \( \pi_V(k) + \lambda \in \text{Vt}(X_{\alpha'}) \). By Lemma 12 there is a \( \hat{\lambda} = \lambda \times j \in \Lambda \times Z \), independent of \( k \), such that \( k + \hat{\lambda} \in \text{Vt}(Y_{(\alpha', v + \lambda, \ell')}) \). By adding \( 0_V \times q \) to \( \hat{\lambda} \) for some \( q \in Z \), we may ensure \( \hat{\lambda} \in \hat{\Lambda} \) and

\[
k + \hat{\lambda} \in \text{Vt}(Y_{(\alpha', v + \lambda, \ell')}),
\]

where \( \ell' := \ell + q \). By again adding \( 0_V \times q' (M_2 - M_1) \) to \( \hat{\lambda} \) for some \( q' \in Z \), we may assume \( \ell' \in [M_1, M_2] \). Note that \( \gamma' = (\alpha', v + \lambda, \ell') \) is independent of \( k \). Using the barycentric expansion \( (vii) \) of \( y \), let

\[
\hat{y} := \sum_{\kappa} c_\kappa (k + \lambda) = y + \hat{\lambda} \in Y_{\gamma'} \subset Y = T(X \times [M_1, M_2]).
\]

As \( y', \hat{y} \in Y \), we can write

\[
y' = T(x' \times t'), \quad \hat{y} = T(\hat{x} \times \hat{t}) \quad (x', \hat{x} \in X, \ t', \hat{t} \in [M_1, M_2]).
\]

Applying the projection \( \pi_Y \) and \( (vii) \), we find

\[
x' = \pi_Y(y') = \pi_Y(y + \lambda) = x + \lambda = \pi_Y(y + \hat{\lambda}) = \pi_Y(\hat{y}) = \hat{x}.
\]

Therefore, using \( (vii) \),

\[
\hat{\lambda} - \hat{\lambda} = y' - \hat{y} = T(x' \times t') - T(x' \times \hat{t}) = x' \times (r_{x'} + t') - x' \times (r_{x'} + \hat{t}) = 0_V \times (t' - \hat{t}).
\]
Since $\tilde{\lambda} - \lambda \in \tilde{\Lambda} := \Lambda \times (M_2 - M_1)Z$ and $t', \hat{t} \in [M_1, M_2]$, there are only three possibilities:

i) $t' = \hat{t}$,

ii) $t' = M_1$, $\hat{t} = M_2$,

iii) $t' = M_2$, $\hat{t} = M_1$.

Note that $t'$ and $\hat{t}$ are independent of $\kappa \in \text{SpVt}(y)$ since $\tilde{\lambda}$ and $\lambda$ are independent of $\kappa$. Hence the same case i), ii) or iii) above occurs, independently of $\kappa$.

In case i), $\lambda = \tilde{\lambda}$, so (65) implies (62) with $\tilde{\gamma} := \gamma'$. In this case we are done. Consider now case ii), so $\tilde{y} = T(\tilde{x} \times M_2)$ and

$$\tilde{\lambda} = \lambda + (0V \times (M_1 - M_2)).$$

Order the vertices $v_j$ of $X_\alpha$ so that $v_0 \prec_\alpha v_1 \prec_\alpha \cdots \prec_\alpha v_p$. Using the notation of (31), let

$$X^{(\alpha, v, \ell), A}_\gamma := (X^{v}_{\alpha, \prec_\alpha})^\pm + (0V \times \ell) \subset X^{(\alpha, v, \ell), A} \quad (\ell \in \mathbb{Z}).$$

From (32) we have

$$(\tilde{x} \times M_2) \subset (X^{(\alpha', v_p, M_2-1), A})^+ \subset X^{(\alpha', v_p, M_2-1), A}.$$

Hence

$$\text{SpVt}(\tilde{x} \times M_2; X^A) \subset (X^{(\alpha', v_p, M_2-1), A})^+,$$

where $X^A$ is the simplicial complex $X^A := \bigcup_\gamma X^\gamma A = X \times [M_1, M_2]$ in (39). Thus,

$$\tilde{y} = T(\tilde{x} \times M_2) \subset T((X^{(\alpha', v_p, M_2-1), A})^+) \subset T(X^{(\alpha', v_p, M_2-1), A}) = Y^{(\alpha', v_p, M_2-1), A}_\gamma.$$

As $\tilde{y} := \sum_\gamma c_\gamma (\kappa + \tilde{\lambda})$ by (60), we see from (63) that

$$\kappa + \tilde{\lambda} \in \text{SpVt}(\tilde{y}) \subset \text{Vt}(T((X^{(\alpha', v_p, M_2-1), A})^+)).$$

By (32) again,

$$(X^{(\alpha', v_p, M_2-1), A})^+ = (X^{(\alpha', v_0, M_1), A})^- + (0V \times (M_2 - M_1)).$$

Applying $T$ and (33) we find

$$T((X^{(\alpha', v_p, M_2-1), A})^+) = T((X^{(\alpha', v_0, M_1), A})^-) + (0V \times (M_2 - M_1)).$$

Using (67), (68) and (69) we obtain

$$\kappa + \tilde{\lambda} = \kappa + \lambda + (0V \times (M_1 - M_2)) \subset \text{Vt}(Y^{(\alpha', v_0, M_1)})^- \subset \text{Vt}(Y^{(\alpha', v_0, M_1)}),$$

proving (62) with $\tilde{\gamma} := (\alpha', v_0, M_1)$.

Case iii) is analogous, for then $\tilde{y} = T(\tilde{x} \times M_1) \in (Y^{(\alpha', v_0, M_1)})^-$ and $\tilde{\lambda} = \lambda + (0V \times (M_2 - M_1))$. Reasoning as above, we find $\kappa + \tilde{\lambda} \in \text{Vt}(Y^{(\alpha', v_p, M_2-1)})$, concluding the proof of Proposition 3.

4. Degree theory and the signed fundamental domain

In this section we prove Theorem 1. Thus we have fixed independent totally positive units $\epsilon_{\ell} \in k$, principal logarithms $\log \epsilon_{\ell}^{(r_1 + \ell)}$ of these units at the complex embeddings, and integers $N_j \geq 3$ ($1 \leq \ell \leq r := r_1 + r_2 - 1$, $1 \leq j \leq r_2$). Lastly, we have also fixed a twister function $\beta : \mathbb{Z}^{n-1} \to k^*$, as defined in (2.3).
4.1. The function \( \tilde{f} \) on \( \tilde{X} \times \mathbb{R} \).

Proposition 13. The \((n-1)\)-complex \( \tilde{X} = \bigcup_{\alpha \in \mathcal{I}} \tilde{X}_\alpha \subset \mathbb{R}^{n-1} \) defined in (22) is a \( \Lambda \)-complex (see Definition 2), where \( \Lambda := \mathbb{Z}^r \times N_1 \mathbb{Z} \times N_2 \mathbb{Z} \times \cdots \times N_r \mathbb{Z} \subset \mathbb{Z}^{n-1} \). It has the following additional properties.

(i) The vertices have integral coordinates, i.e. \( Vt(\tilde{X}_\alpha) \subset \mathbb{Z}^{n-1} \) for all \( \alpha \in \mathcal{I} \).

(ii) There are \( |\mathcal{I}| = (n-1)! \prod_{j=1}^{2} N_j \) simplices \( \tilde{X}_\alpha \).

(iii) For any integer \( 1 \leq j \leq r_2 \) and any index \( \alpha \in \mathcal{I} \), there is an \( \alpha_j \in \mathbb{R} \) such that any \( \kappa \in \tilde{X}_\alpha \) satisfies \( \alpha_j \leq \Omega_j(\kappa) \leq \alpha_j + 1 \), where

\[
\Omega_j(\kappa) := \kappa[r + j] + \frac{N_j}{2\pi} \sum_{\ell=1}^{r} \kappa[\ell] \arg(\epsilon^{(r_1+j)}_{\ell}) \quad (\kappa = (\kappa[1], \ldots, \kappa[n-1]) \in \mathbb{R}^{n-1})
\]

and \(-\pi < \arg(\epsilon^{(r_1+j)}_{\ell}) \leq \pi \).

Proof. Recall from (22) that \( \tilde{X} := X_{n-1} \) was constructed inductively starting from the trivial one-point complex \( X_0 \), letting

\[ X_j := Y(X_{j-1}, \omega_{j-1}, [0, Q_j]) \]

where \( Q_j := 1 \), \( \omega_{j-1}(x) := 0 \) if \( 1 \leq j \leq r \), and

\[ Q_{r+j} := N_j, \quad \omega_{r+j-1}(x) := \frac{N_j}{2\pi} \sum_{\ell=1}^{r} x[\ell] \arg(\epsilon^{(r_1+j)}_{\ell}) \quad (1 \leq j < r_2). \]

Since \( X_0 \) is obviously a \( \Lambda_0 \)-complex for the trivial lattice \( \Lambda_0 := \{0\} \), Proposition 3 and induction on \( j \) shows that \( X_j \subset \mathbb{R}^j \) is a \( Q_1 \mathbb{Z} \times \cdots \times Q_j \mathbb{Z} \)-complex for \( 1 \leq j \leq n-1 \).

Taking \( j = n-1 \) shows that \( \tilde{X} \) is a \( \Lambda \)-complex.

Property (i) in Proposition 13 was already proved in (13), while (ii) follows from (5). To prove (iii), let \( \kappa \in \tilde{X}_\alpha \) and let \( \pi_{r+j} : \mathbb{R}^{n-1} \to \mathbb{R}^r \) be the projection to the first \( r + j \) coordinates \((1 \leq j \leq r_2)\). Then \( \pi_{r+j}(\kappa) \) is contained in some \((r+j)\)-simplex \( Y_\gamma := \pi_{r+j}(\tilde{X}_\alpha) \subset X_{r+j} \) for some index \( \gamma = (\beta, v, \ell) \) depending on \( j \) and \( \alpha \). Here the complex \( X_{r+j} \) was defined in (11), \( v \) is a vertex in a simplex in \( X_{j+r-1} \) indexed by \( \beta \), and \( \ell \) is an integer in the range \( 0 \leq \ell < N_j \). Inequality (38) in Proposition 3 applied to \( \pi_{r+j}(\kappa) \in Y_\gamma \), to \( X := X_{r+j-1}, V = \mathbb{R}^{r+j-1}, \omega := \omega_{r+j-1} \) and to \([M_1, M_2] := [0, N_j]\), yields (iii) with \( \alpha_j := A(v) + \ell - 1 \) and \( A(v) \) as in (38).

We now define the function \( \tilde{f} \) in (11). Henceforth we keep the notation of Proposition 13 i.e. \( \tilde{X}, \mathcal{I}, \Lambda \) and \( \Omega_j \). For \( \alpha \in \mathcal{I} \), let \( A_\alpha : \mathbb{R}^{n-1} \to \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \) be the unique affine function which on vertices \( v = (v[1], \ldots, v[n-1]) \in Vt(\tilde{X}_\alpha) \subset \mathbb{Z}^{n-1} \) is given by

\[
A_\alpha(v) := \tilde{f}(v) := \beta(v) \prod_{\ell=1}^{r} \epsilon^{(r_1+j)}_{\ell} \subset \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}.
\]

Here we used (i) of Proposition 13 and the twister function \( \beta \) recalled at the beginning of this section. Note that since by definition \( \beta \) is \( \Lambda \)-periodic,

\[
\tilde{f}(v + \lambda) = \tilde{f}(v) \prod_{\ell=1}^{r} \epsilon^{(r_1+j)}_{\ell} \quad (v \in \mathbb{Z}^{n-1}, \lambda \in \Lambda).
\]

\footnote{We identify \( 0 \times \mathbb{R}^j \) with \( \mathbb{R}^j \), of course.}
Let \( A : \mathfrak{X} \to \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \) be the piecewise affine function which equals \( A_\alpha \) on \( \mathfrak{X}_\alpha \).

Since \( \mathfrak{X} = \bigcup_{\alpha \in \mathfrak{I}} \mathfrak{X}_\alpha \) is a simplicial complex by Proposition 13, and \( \hat{f}(v) \) in (44) does not depend on \( \alpha \in \mathfrak{I} \), the \( A_\alpha \) define a unique (and continuous) piecewise affine function \( A : \mathfrak{X} \to \mathbb{R} \) which restricts to \( A_\alpha \) on \( \mathfrak{X}_\alpha \). Let

\[
(73) \quad f(x \times y) := \varepsilon^y A(x), \quad f : \mathfrak{X} \times \mathbb{R} \to \mathbb{R}^{r_1} \times \mathbb{C}^{r_2},
\]

where \( \varepsilon^y \) is regarded as a real scalar multiplying each one of the \( r_1 + r_2 \) coordinates of \( A(x) \). Writing \( x = \sum_{i=0}^{n-1} c_i v_i \), where \( \sum_{i=0}^{n-1} c_i = 1 \), \( c_i \geq 0 \) (0 \leq i \leq n - 1), (24) gives

\[
(74) \quad f(x \times y) = \varepsilon^y \sum_{i=1}^{n} c_i w_i \quad (x \in \mathfrak{X}_\alpha = [v_0, ..., v_{n-1}], \ y \in \mathbb{R}, \ w_i := \hat{f}(v_i)).
\]

We now prove some basic properties of \( f \).

**Lemma 14.** The function \( f \) defined in (73) above has the following properties.

\[
(75) \quad (i) \quad f(\mathfrak{X}_\alpha \times \mathbb{R}) \subset \mathcal{H}_\alpha := \mathbb{R}^{r_1}_+ \times H(\frac{\alpha_1 + \frac{1}{2}}{N_1}) \times \cdots \times H(\frac{\alpha_{r_2} + \frac{1}{2}}{N_{r_2}}),
\]

where \( \alpha_j \in \mathbb{R} \) was defined in Proposition 13 (iii) and where \( H(t) \subset \mathbb{C}^* \) is the open half-plane

\[
H(t) := \{ re^{2\pi i(t+\theta)} \in \mathbb{C}^* \mid r > 0, \ \theta \in (-1/4, 1/4) \}.
\]

Thus,

\[
(76) \quad f(\mathfrak{X} \times \mathbb{R}) \subset \mathbb{R}^{r_1}_+ \times \mathbb{C}^{r_2}.
\]

(ii) For \( \alpha \in \mathfrak{I} \), let \( v_0, ..., v_{n-1} \) be the vertices of \( \mathfrak{X}_\alpha \) (in any order) and let \( w_i := \hat{f}(v_i) = f(v_i \times 0) \in k \subset \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \), and let \( \overline{C}_\alpha \) be as defined in (19). Then

\[
(77) \quad \overline{C}_\alpha = f(\mathfrak{X}_\alpha \times \mathbb{R}) = \left\{ t_0 w_0 + t_1 w_1 + \cdots + t_{n-1} w_{n-1} \mid t_i \geq 0 \ for \ 0 \leq i \leq n - 1 \right\} - \{0\},
\]

the closed \( k \)-rational polyhedral cone generated by the \( w_i \), minus the origin.

(iii) If \( y \in \mathbb{R} \) and \( x' = x + \lambda \) with \( x, x' \in \mathfrak{X} \) and \( \lambda \in \Lambda \) (see Proposition 13), then

\[
(78) \quad f(x' \times y) = \varepsilon(\lambda) f(x \times y), \quad \varepsilon(\lambda) := \prod_{\ell=1}^{r} \varepsilon^{\lambda[\ell]} (\lambda = (\lambda[1], ..., \lambda[n-1])).
\]

Note that \( \varepsilon(\lambda) \) is a unit belonging to the subgroup generated by \( \varepsilon_1, ..., \varepsilon_r \). The product \( \varepsilon(\lambda) f(x \times y) \) is taken in the ring \( \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \). Recall that we regard \( k \subset \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \).

**Proof.** We begin with the proof of (19), i.e. \( f(\mathfrak{X}_\alpha \times \mathbb{R}) \subset \mathcal{H}_\alpha \). The set \( \mathcal{H}_\alpha \) is a convex cone, so from (14) it is clear that it suffices to prove \( f(\kappa \times 0) \in \mathcal{H}_\alpha \) for \( \kappa \in \text{vt}(\mathfrak{X}_\alpha) \). From (12) and (14),

\[
(79) \quad f(\kappa \times 0)^{(j)} = \beta(\kappa)^{(j)} \prod_{\ell=1}^{r} (\varepsilon^{\lambda[\ell]})(\kappa[\ell]) \quad (1 \leq j \leq r_1 + r_2).
\]
For $1 \leq j \leq r_1$, $\beta(k)^{(j)} > 0$ and $\varepsilon_j^{(j)} > 0$, so $f(k \times 0)^{(j)} > 0$. For $1 \leq j \leq r_2$, recall from (13) in the definition of twisters,

\[(80) \quad \beta(k)^{(r_1+j)} = |\beta(k)^{(r_1+j)}| \exp\left(2\pi i (k[r+j] + t_j(k))/N_j\right) \left(\frac{|t_j(k)|}{N_j} < \frac{1}{4} - \frac{1}{2N_j}\right).\]

Using Proposition 13 (iii) and (10), we can write

\[(81) \quad \Omega_j(k) := k[r+j] + \frac{N_j}{2\pi} \sum_{\ell=1}^r \kappa[\ell] \arg(\varepsilon_\ell^{(r_1+j)}) = \alpha_j + \frac{1}{2} + \theta_j(k)\]

for some $\theta_j(k) \in [-1/2, 1/2]$. Then, letting $r_j(k) := |\tilde{f}(k)^{(r_1+j)}| > 0$, from (79) we have

\[
\tilde{f}(k)^{(r_1+j)} \\
= r_j(k) \exp\left(2\pi i (k[r+j] + t_j(k))/N_j\right) \left(\frac{i}{2N_j} \sum_{\ell=1}^r \kappa[\ell] \arg(\varepsilon_\ell^{(r_1+j)})\right) \exp\left(2\pi i t_j(k)/N_j\right) \\
= r_j(k) \exp\left(2\pi i \Omega_j(k)/N_j\right) \exp(2\pi i t_j(k)/N_j) \\
= r_j(k) \exp\left(2\pi i (\alpha_j + \frac{1}{2})/N_j\right) \exp(2\pi i t_j(k) + \theta_j(k)/N_j) .
\]

By (80) and (81), $|t_j(k) + \theta_j(k)|/N_j < \frac{1}{4}$, showing that $\tilde{f}(k)^{(r_1+j)} \in H\left((\alpha_j + \frac{1}{2})/N_j\right)$ and proving (77).

To prove (78), write the barycentric expansion of $x = \sum_i c_i v_i \in X_\alpha$, but only include vertices $v_i$ with $c_i > 0$, i.e. $v_i \in \text{SpVt}(x)$. Since $X$ is a $\Lambda$-complex by Proposition 13, every $v_i + \lambda$ is a spanning vertex of $x'$, and therefore a vertex of some $X_\alpha'$ where $\alpha'$ is independent of $v_i$ (see property (v) in Definition 2). Hence we obtain the barycentric expansion of $x'$ as

\[x' = x + \lambda = \lambda + \sum_i c_i v_i = \sum_i c_i (v_i + \lambda) .\]

By (74) and (72),

\[f(x' \times y) = e^y \sum_i c_i \tilde{f}(v_i + \lambda) = e^y \sum_i c_i \tilde{f}(v_i) \varepsilon(\lambda) = \varepsilon(\lambda) f(x \times y) ,\]

proving (75).

We now prove (77). Since $f(x \times 0) = A_\alpha(x)$ for $x \in X_\alpha$, and $A_\alpha$ is an affine function, it follows that $f(X_\alpha \times 0) = [w_0, ..., w_{n-1}]$, the convex hull of the $w_i := A_\alpha(v_i)$. From (13), $f(x \times y) = e^y f(x \times 0)$. It follows that $f(X_\alpha \times \mathbb{R}) \subset H_\alpha$ is the closed cone generated by the $w_i$, minus the origin. It does not contain the origin since $0 \notin H_\alpha$.

\[\square\]

4.2. Global and local degree computations. As in Theorem 1 let $\varepsilon_1, \ldots, \varepsilon_r$ be fixed independent totally positive units of $k$, where $r = r_1 + r_2 - 1$. We use them to define a homomorphism $g$ from the additive group $\mathbb{R}^n$ to the multiplicative
Lemma 17. Namely, let the $j$-th coordinate of $g$ ($1 \leq j \leq r_1 + r_2$) be
\begin{equation}
(82) \quad g(x)^{(j)} := \begin{cases} 
\exp\left(x[n] + \sum_{\ell=1}^{r_1} x[\ell] \log \epsilon_{\ell}^{(j)} \right) & \text{if } j \leq r_1, \\
\exp\left(x[n] + \frac{\pi i x[j] + 1}{N_{j-r_1}} + \sum_{\ell=1}^{r_1} x[\ell] \log \epsilon_{\ell}^{(j)}\right) & \text{if } r_1 < j.
\end{cases}
\end{equation}
Here $N_j$ is as in Theorem 1 and $\log$ denotes the branch with $-\pi < \text{Im}(\log z) \leq \pi$.

Lemma 15. The homomorphism $g$ in \((82)\) is onto, infinitely differentiable and
\begin{equation}
(83) \quad g^{-1}(\langle \varepsilon_1, \ldots, \varepsilon_r \rangle) = \hat{\Lambda} := \Lambda \times 0 = \mathbb{Z}^r \times N_1 \mathbb{Z} \times \cdots \times N_r \mathbb{Z} \times 0 \subset \mathbb{R}^n,
\end{equation}
where $\langle \varepsilon_1, \ldots, \varepsilon_r \rangle$ is the subgroup of the units of $k$ generated by the $\varepsilon_i$.

Proof. From \((82)\) it is clear that $g$ is infinitely differentiable. Let us show that $g$ is onto. Let $\{E_i\}_{i=1}^n$ be the standard basis for $\mathbb{R}^n$. Then $g(E_i) = \varepsilon_i$ for $1 \leq i \leq r$, and $g(E_0) = (e, \ldots, e)$. Define $L : \mathbb{R}^r_+ \times \mathbb{C}^{*r_2} \to \mathbb{R}^{r_1 + r_2}$ at $z = (z(1), \ldots, z(r_1 + r_2))$ by
\begin{equation}
(84) \quad (L(z))_j := e_j \log |z(j)| \quad (e_j := 1 \text{ if } 1 \leq j \leq r_1, \quad e_j := 2 \text{ if } r_1 < j \leq r_1 + r_2).
\end{equation}
Then $L(g(x)) = x[n]F + \sum_{\ell=1}^{r_1} x[\ell]L(\varepsilon_\ell)$, where $F_j := \varepsilon_j$. As the $\varepsilon_i$ are assumed independent and $F$ does not lie in the span of the $L(\varepsilon_i)$, given $z \in \mathbb{R}^r_+ \times \mathbb{C}^{*r_2}$, there exists $x \in \mathbb{R}^n$ such that $L(g(x)) = L(z)$. But then all coordinates of $z g(-x) \in \mathbb{R}^r_+ \times \mathbb{C}^{*r_2}$ have absolute value 1, so $x(j) = g(x)^{(j)} \exp(2\pi i \theta_j)$ with $\theta_j \in \mathbb{R} (r_1 < j \leq r_1 + r_2)$. On letting $x'(\ell) := x[\ell] + N_{r_1-\ell} \theta_{r_1-\ell+1}$ for $r < \ell \leq n - 1$ and $x'(r) := x[r]$ for all other $\ell$, we have $g(x') = z$.

A similar use of $L$ shows that $x \in \ker(g)$ if and only if $x[j] = 0$ for $1 \leq j \leq r$ and $j = n$, and $x[r+j] \in N_j \mathbb{Z}$ for $1 \leq j \leq r_2$. Hence \((83)\) follows. \hfill \square

Lemma 16. With $g$ and $\mathcal{H}_\alpha$ as in \((82)\) and \((75)\), $g(\mathcal{X}_\alpha \times \mathbb{R}) \subset \mathcal{H}_\alpha$.

Proof. For $1 \leq j \leq r_1$ it is clear that $g(x \cdot y)^{(j)} > 0$ for $x \in \mathbb{R}^{n-1}$ and $y \in \mathbb{R}$. For $1 \leq j \leq r_2$, observe that $g(x \cdot y)^{(r_1+j)} = e^y g(x \cdot 0)^{(r_1+j)}$. Hence it suffices to show that $g(x \cdot 0) \in \mathcal{H}_\alpha$ for $x \in \mathcal{X}_\alpha$. Now $g(x \cdot 0)^{(r_1+j)} = r_{x,j} \exp(2\pi i \Omega_j(x)/N_j)$, where $r_{x,j} > 0$ and $\Omega_j(x)$ was defined in \((70)\). Property (iii) in Proposition 13 concludes the proof since $N_j \geq 3$ by assumption. \hfill \square

Let $\hat{\Lambda} \subset \mathbb{R}^n$ be as in \((83)\), and define the $n$-manifolds
\begin{equation}
(85) \quad \hat{T} := \mathbb{R}^n/\hat{\Lambda}, \quad T := (\mathbb{R}^r_+ \times \mathbb{C}^{*r_2})/\langle \varepsilon_1, \ldots, \varepsilon_r \rangle.
\end{equation}

It follows from Lemma 15 that $g$ induces a bijection $G : \hat{T} \to T$,
\begin{equation}
(86) \begin{array}{ccc}
\mathbb{R}^n & \xrightarrow{g} & \mathbb{R}^r_+ \times \mathbb{C}^{*r_2} \\
\hat{T} & \xrightarrow{\hat{g}} & T \\
T & \xrightarrow{G} & T
\end{array}
\end{equation}
making the diagram commute. Here $\hat{g}$ and $\pi$ are the natural quotient maps.

Lemma 17. The map $G : \hat{T} \to T$ defined above is a homeomorphism.

Proof. Since $\hat{T}$ is not compact, it is not quite obvious that $G^{-1}$ is continuous. But, as $G$ is a continuous and bijective map between locally compact metric spaces, it
suffices to prove that $G$ is proper. Thus, let $K \subset T$ be compact, and let us show that $G^{-1}(K) \subset \tilde{T}$ is compact. Define the “norm” map $\mathcal{N} : \mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2} \to \mathbb{R}_+$ by
\[
(87) \quad \mathcal{N}(z) := \prod_{j=1}^{r_1+r_2} |z^{(j)}|^{e_j} \quad (z = (z^{(1)}, \ldots, z^{(r_1+r_2)})),
\]
with $e_j = 1$ or 2 as in \[(84)\]. Then $\mathcal{N}(\varepsilon_i) = 1$ $(1 \leq i \leq r)$, so $\mathcal{N}$ induces a continuous map $\tilde{\mathcal{N}} : T \to \mathbb{R}_+$. Since $K$ is compact, $\tilde{\mathcal{N}}(K) \subset [a, b]$ for some positive real numbers $a$ and $b$. As $\mathcal{N}(g(x[1], \ldots, x[n])) = e^{nx[n]}$, we have by Lemma \[15\] and \[53\],
\[
G^{-1}(K) \subset \tilde{\mathcal{N}}\left([0, 1]^r \times [0, N_1] \times \cdots \times [0, N_{r_2}] \times [(\log a)/n, (\log b)/n]\right),
\]
a compact subset of $T$.

From Lemma \[17\] and $\tilde{T} := \mathbb{R}^n/\mathbb{R}$, it is clear that $\tilde{T}$ and $T$ are homeomorphic to an $(n-1)$-torus $\times \mathbb{R}$. Thus, $G$ is a homeomorphism between connected, orientable $n$-manifolds. We fix any orientation of $\mathbb{R}^n$ and orient $\mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2}$ by declaring the homeomorphism $I : \mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2} \to \mathbb{R}^n$,
\[
(88) \quad I(z_1, \ldots, z_{r_1+r_2}) := (z_1, \ldots, z_{r_1}, \text{Re}(z_{r_1+1}), \text{Im}(z_{r_1+1}), \ldots, \text{Re}(z_{r_1+r_2}), \text{Im}(z_{r_1+r_2})),
\]
to be orientation-preserving. The orientation on $\mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2}$ induces an orientation on its open subset $\mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2} = \text{domain}(\pi)$. Finally, we orient $\tilde{T}$ and $T$ by declaring $\pi$ and $\tilde{\pi}$ in \[55\] to be orientation-preserving.

In practice, this means for the homeomorphism $G$ that $\deg(G) = \pm 1$ is the sign of the determinant of the Jacobian matrix $\text{Jac}_x(I \circ g)$ of $I \circ g : \mathbb{R}^n \to \mathbb{R}^n$ at any point $x$ of its domain, a number which we now compute\footnote{The degree of any (proper, continuous) function from an oriented manifold $L$ to itself is independent of the orientation on $L$. Thus, $\deg(I \circ g)$ is independent of the orientation of $\mathbb{R}^n$ fixed above. A summary of degree theory in five pages, based on Dold’s textbook \[15\] and sufficient for our purposes, can be found in \[12\] §7.}.

Lemma 18. With the orientation on $\tilde{T}$ and $T$ defined above,
\[
\deg(G) = (-1)^{n-1}(-1)^{r_2(r_2-1)/2} \text{sign} (\det(R)) \neq 0,
\]
where $R = (r_{ij})$ is the matrix defined in \[17\].

Proof. We have $\det(R) \neq 0$ since the rows with $i > 1$ span the hyperplane
\[
\{x = (x_j) \in \mathbb{R}_+^{r_1+r_2} | x_1 + \cdots + x_{r_1} + 2x_{r_1+1} + \cdots + 2x_{r_1+r_2} = 0\},
\]
while the first row is off the hyperplane. Since $G$ is a homeomorphism, $\deg(G) = \text{locdeg}_p(\tilde{T})$, the local degree at any $p \in \tilde{T}$ \[39\] as $\tilde{\pi}$ and $\pi$ are orientation-preserving local homeomorphisms, $\deg(G) = \text{locdeg}_x(g)$ for any $x \in \mathbb{R}^n$. By definition of the orientation on $\mathbb{R}_+^{r_1} \times \mathbb{C}^{r_2}$, $\text{locdeg}_x(g) = \text{locdeg}_x(I \circ g)$, with $I$ as in \[55\]. If the differential $d(I \circ g)_x : \mathbb{R}^n \to \mathbb{R}^n$ is invertible at some $x$, then \[12\] Prop. 22
\[
\deg(G) = \text{locdeg}_x(I \circ g) = \text{sign} (\det(d(I \circ g)_x)) = \pm 1.
\]

To compute the sign of $\det(Jac_x(I \circ g))$, note that \[52\] and \[55\] show that the coordinates corresponding to $1 \leq j \leq r_1$ are
\[
((I \circ g)(x))_j = e^{x[n] + \sum_{i=1}^{r_1} x[i] |c_i^{(j)}|} = e^{x[n] + \sum_{i=1}^{r_1} x[i] \log |c_i^{(j)}|}
\]
and
It is now easy to calculate the matrix of $g(x)^{(j)}$. Thus, setting $\Theta^{(j)} := \arg(e^{(j+r_1)})$ for $1 \leq j \leq r_2$, 

$$(\mathcal{I} \circ g)(x)_{2j-1+r_1} = e^{x[n]+\sum_{\ell=1}^r x[\ell]\log|\varepsilon^{(j)}|} \cos(\frac{2\pi x[j+r_1]}{N_1} + \sum_{\ell=1}^r x[\ell] \Theta^{(j)}),$$

$$((\mathcal{I} \circ g)(x)_{2j+r_1} = e^{x[n]+\sum_{\ell=1}^r x[\ell]\log|\varepsilon^{(j)}|} \sin(\frac{2\pi x[j+r_1]}{N_1} + \sum_{\ell=1}^r x[\ell] \Theta^{(j)}).$$

It is now easy to calculate the matrix $J := \text{Jac}_x(\mathcal{I} \circ g)$. Namely, abbreviating $L^{(j)}_\ell := \log|\varepsilon^{(j)}|_\ell$ (1 \leq j \leq r_1, 1 \leq \ell \leq r),

$J = \begin{pmatrix}
L^{(1)}_1 & \cdots & L^{(r_1)}_1 & \Theta^{(1)}_1 & \cdots & L^{(r_1+r_2)}_1 & \Theta^{(r_2)}_1 \\
L^{(1)}_2 & \cdots & L^{(r_1)}_2 & \Theta^{(1)}_2 & \cdots & L^{(r_1+r_2)}_2 & \Theta^{(r_2)}_2 \\
\vdots & \cdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
L^{(1)}_r & \cdots & L^{(r_1)}_r & \Theta^{(1)}_r & \cdots & L^{(r_1+r_2)}_r & \Theta^{(r_2)}_r \\
0 & \cdots & 0 & 0 & 2\pi/N_1 & \cdots & 0 & 0 \\
\vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\
0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 2\pi/N_2 \\
1 & \cdots & 1 & 1 & 0 & \cdots & 1 & 0
\end{pmatrix}.$

To compute $\det(J)$, permute the rows so that the bottom row becomes the first row, and row $i$ becomes row $i+1$ (1 \leq i \leq n-1). This introduces a factor of $(-1)^{n-1}$. Now permute columns so that all columns coming from imaginary parts at complex places are placed to the right of all those coming from the real parts (with the places in the same relative order as before). This gives a factor of $(-1)^{\sum_{j=1}^r j} = (-1)^{r_2(r_2-1)/2}$, and results in a lower-right $r_2 \times r_2$ diagonal block and a lower-left block of 0’s of size $r_2 \times (r_1 + r_2)$. Hence,

$$\det(J) = (-1)^{n-1}(-1)^{r_2(r_2-1)/2} \det(R) \prod_{j=1}^{r_2} (2\pi/N_j) \neq 0,$$

from which the lemma follows. \hfill \Box

We now incorporate the map $f$ of Lemma 14 into our maps between manifolds. By (76) and (78), $f$ induces a (continuous) map $F: \tilde{T} \to T$ making

$$\begin{CD}
\mathfrak{X} \times \mathbb{R} @>f>> \mathbb{R}^{r_1}_+ \times \mathbb{C}^{r_2} \\
| \varepsilon @>>\pi>> | \varepsilon \\
\tilde{T} @>F>> T
\end{CD}$$

a commutative diagram (89), where $\tilde{T}$, $\tilde{\varepsilon}$, $T$ and $\pi$ are as in (88).

**Lemma 19.** Fix the orientation on $\tilde{T}$ and $T$ as in Lemma 18. Then $F$ in (89) is a proper map and

$$\deg(F) = \deg(G) = (-1)^{n-1}(-1)^{r_2(r_2-1)/2} \text{sign}(\det(R)) = \pm 1.$$

**Proof.** By Lemma 18, it suffices to prove that $F$ is proper and that $\deg(F) = \deg(G)$. This will follow once we construct a proper homotopy between $G$ and $F$. Suppose $x \times y \in \mathfrak{X} \times \mathbb{R}$. Then $x \in \mathfrak{X}_\alpha$ for some $\alpha \in \mathcal{J}$. By Lemmas 14 and 16 both
As a unique affine function such that $f(x \times y) = e^y f(x \times 0)$ and $g(x \times y) = e^y g(x \times 0)$. For $x \in X$, $y \in \mathbb{R}$ and $\lambda \in \Lambda := \mathbb{Z}^r \times \mathbb{Z}^N_1 \times \cdots \times \mathbb{Z}^N_r$, we have by \((78)\) and \((82)\),

\[
(90) \quad f((x + \lambda) \times y) = \varepsilon(\lambda) f(x \times y), \quad g((x + \lambda) \times y) = \varepsilon(\lambda) g(x \times y).
\]

As $\varepsilon(\lambda) \in E := \langle \varepsilon_1, \ldots, \varepsilon_r \rangle$, the homotopy $\vartheta$ descends to the quotient manifolds,

$$
\Theta : \hat{T} \times [0, 1] \to T, \quad \Theta(\tilde{\vartheta}(x \times y) \times t) = \pi(\vartheta(x \times y \times t)).
$$

Since $\Theta$ provides a homotopy between $F$ and $G$, our only remaining task is to show that $\Theta$ is a proper map [DFP2 Prop. 21 (4)]. To this end, let $K \subset T$ be compact. We must prove that $\hat{K} := \Theta^{-1}(K) \subset \hat{T} \times [0, 1]$ is compact. From this it will follow that $F$ is proper, since $F^{-1}(K) = \{\tilde{x} \in \hat{T} | \tilde{x} \times 1 \in \Theta^{-1}(K)\}$.

As the $\lambda$-complex $X \subset \mathbb{R}^{n-1}$ is nearly a fundamental domain for $\Lambda$ (see \((iv)\) in Definition \[2\]),

\[
(91) \quad \hat{\pi}(X \times \mathbb{R}) = \hat{T},
\]

so it suffices to prove the compactness of

$$
\mathcal{K} := \hat{\pi}^{-1}(\hat{K}) = \vartheta^{-1}(\pi^{-1}(K)) \subset X \times \mathbb{R} \times [0, 1].
$$

As in the proof of Lemma \[17\], $\hat{N}(K) \subset [a, b]$ for some $a, b > 0$. Since $L := \pi(\vartheta(X \times 0 \times [0, 1]))$ is a compact subset of $T$, $\hat{N}(L) \subset [c, d]$ for some $c, d > 0$. If $x \times y \times t \in \mathcal{K}$, then

$$
[a, b] \ni \hat{N}(\pi(\vartheta(x \times y \times t))) = e^{ny} \hat{N}(\pi(\vartheta(x \times 0 \times t))) \in e^{ny}[c, d].
$$

It follows that $\frac{1}{n} \log(a/d) \leq y \leq \frac{1}{n} \log(b/c)$. Thus, $y$ is bounded and $\mathcal{K}$ is compact.

We now calculate another Jacobian determinant.

**Lemma 20.** Given $n$ affinely independent elements $v_0, v_1, \ldots, v_{n-1} \in \mathbb{R}^{n-1}$, and any $n$ elements $w_0, w_1, \ldots, w_{n-1} \in \mathbb{R}^r \times \mathbb{C}^2$, let $B : \mathbb{R}^{n-1} \to \mathbb{R}^r \times \mathbb{C}^2$ be the unique affine function such that $B(v_i) = w_i$ ($0 \leq i \leq n-1$). Define $K : \mathbb{R}^n \to \mathbb{R}^n$ by

$$
K(x[1], \ldots, x[n]) := \mathcal{I}(e^{x[n]} B(x[1], \ldots, x[n-1])),
$$

where the linear isomorphism $\mathcal{I} : \mathbb{R}^r \times \mathbb{C}^2 \to \mathbb{R}^n$ was defined in \((88)\). Then

\[
(92) \quad \det(\text{Jac}_x(K)) = (-1)^{n-1} e^{nx[n]} \det(W) / \det(V)
\]

where $x = (x[1], \ldots, x[n]) \in \mathbb{R}^n$, $W$ is the $n \times n$ matrix whose $i$-th column is $\mathcal{I}(w_{i-1})$ ($1 \leq i \leq n$), and $V$ is the invertible $(n-1) \times (n-1)$ matrix whose $i$-th column is $v_i - v_0$ ($1 \leq i \leq n-1$).
Proof. The matrix $V$ is invertible since, by definition of affine independence, the $v_i - v_0$ ($1 \leq i \leq n - 1$) are linearly independent. By (21), $B$ satisfies $B(\sum_{i=1}^{n} y_i v_i) = \sum_{i=1}^{n} y_i w_i$ provided $\sum_{i=1}^{n} y_i = 1$, $y_i \in \mathbb{R}$. Let $E_n := (0, 0, ..., 0, 1) \in \mathbb{R}^n$ and $\tilde v_i := v_i \times 0 \in \mathbb{R}^n$. Then, for $1 \leq i \leq n - 1$,

$$U(x[1], ..., x[n]) := x[n] E_n + \tilde v_0 + \sum_{i=1}^{n-1} x[i](\tilde v_i - \tilde v_0).$$

Then, for $1 \leq j \leq r_1$,

$$(K \circ U(x))[j] = e^{x[n]}(w_0^{(j)} + \sum_{i=1}^{n-1} x[i](w_i - w_0)^{(j)}) ,$$

while for $1 \leq j \leq r_2$,

$$(K \circ U(x))[2j - 1 + r_1] = e^{x[n]}(\text{Re}(w_0^{(r_1+j)}) + \sum_{i=1}^{n-1} x[i]\text{Re}((w_i - w_0)^{(r_1+j)})),

(K \circ U(x))[2j + r_1] = e^{x[n]}(\text{Im}(w_0^{(r_1+j)}) + \sum_{i=1}^{n-1} x[i]\text{Im}((w_i - w_0)^{(r_1+j)})).$$

The above formulas and elementary row operations yield

$$\det(\text{Jac}_x(K \circ U)) = e^{nx[n]}(-1)^{n-1} \det(I(w_0), ..., I(w_n)) = e^{nx[n]}(-1)^{n-1} \det(W).$$

Now,

$$\det(\text{Jac}_x(K \circ U)) = \det(\text{Jac}_{U(x)}(K)) \det(\text{Jac}_x(U)) = \det(\text{Jac}_{U(x)}(K)) \det(V),$$

so

$$\det(\text{Jac}_{U(x)}(K)) = e^{nx[n]}(-1)^{n-1} \frac{\det(W)}{\det(V)} = e^{nU(x)[n]}(-1)^{n-1} \frac{\det(W)}{\det(V)}.$$ 

Since $U$ is surjective, the proof is done. \hfill \square

We now use (89) to calculate the local degree of $F$.

Lemma 21. Let $\tilde x = \tilde x(x) \in \hat T$, where $x = \kappa \times y \in \mathcal{X}_\alpha \times \mathbb{R}$, let $v_0, ..., v_{n-1}$ be the vertices of $\mathcal{X}_\alpha$ (in any order) and let $w_i := f(v_i \times 0)$. Assume that the $w_i$ are \mathbb{R}-linearly independent and that $\kappa$ is an interior point of $\mathcal{X}_\alpha$. Then the local degree of $F$ at $\tilde x$ is defined and

$$(93) \quad \text{locdeg}_{\tilde x}(F) = (-1)^{n-1} \text{sign}(\det(V)) \text{sign}(\det(W)) =: d_\alpha,$$

with $V$ and $W$ as in Lemma 20.

Proof. By Lemma 20 and the inverse function theorem, $f$ is a local homeomorphism in a neighborhood of $x$, so locdeg$_x(f) = \pm 1$ is defined. Note that deg($I$) = 1 as $I$ in (88) is an orientation-preserving homeomorphism, by definition of the orientation of $\mathbb{R}^n_+ \times \mathbb{C}^{r_2}$. Hence (20) shows that locdeg$_x(f)$ is given by the right-hand side of (93). Here we used the fact that the local degree is invariant under composition with orientation-preserving local homeomorphisms [DF2 Prop. 21 (7)].

We now consider the commutative diagram (89). Note that $\tilde x$ is a local orientation-preserving homeomorphism in a neighborhood of $x$ since $\mathcal{X}$ is nearly a fundamental
domain (see property (iv) in Definition 2). The same holds for the covering map \( \pi \) at any point of its domain, and in particular at \( f(x) \). Thus, \( \text{locdeg}_x(f) = \text{locdeg}_y(f) \).

Next we prove that the number of points in any orbit \( E \cdot x \) inside a cone \( \overline{C}_\alpha \) is bounded independently of \( x \), as claimed at the end of Theorem 1.

**Lemma 22.** Let \( \overline{C}_\alpha := f(\mathfrak{X}_\alpha \times \mathbb{R}) \) be the cone in (77) and let \( E := \langle \varepsilon_1, \ldots, \varepsilon_r \rangle \) be the subgroup of the units of \( k \) generated by the \( \varepsilon_\ell \). Then there exists \( c_\alpha \in \mathbb{N} \) such that for any \( z \in \mathbb{R}^n \times \mathbb{C}^{*r^2} \), the orbit \( E \cdot z \) has at most \( c_\alpha \) elements in \( \overline{C}_\alpha \). Moreover, given any compact subset \( K \subset \mathbb{R}_+^n \times \mathbb{C}^{*r^2} \), there are at most finitely many \( \varepsilon \in E \) such that \( \varepsilon K \cap \overline{C}_\alpha \neq \emptyset \).

**Proof.** We begin by proving the first claim. Let \( N \) be the “norm” map defined in (87). As \( \overline{C}_\alpha \) is a cone, the map \( z \mapsto z^\dagger := N(z)^{-1/n} z \) gives a bijection between \( (E \cdot z) \cap \overline{C}_\alpha \) and \( (E \cdot z^\dagger) \cap \overline{C}_\alpha \). Hence we may assume \( N(z) = 1 \).

Let \( m \) and \( M \) be respectively the minimum and maximum values of \( N \) on the convex hull \( \{w_0, \ldots, w_{n-1}\} \) of the generators \( w_i \) of \( \overline{C}_\alpha \). Then \( m, M \) > 0, and by homogeneity we have

\[
m \left( \sum_{i=0}^{n-1} t_i \right)^n \leq N \left( \sum_{i=0}^{n-1} t_i w_i \right) \leq M \left( \sum_{i=0}^{n-1} t_i \right)^n \quad (t_i \geq 0, \ 0 \leq i \leq n-1).
\]

Hence \( \Gamma := \ker(N) \cap \overline{C}_\alpha \) is compact. Applying the logarithmic map \( \ln \) in (83), we are reduced to bounding the number of \( \varepsilon \in E \) such that \( \ln(\varepsilon) + L(\varepsilon) \in L(\Gamma) \). This is bounded independently of \( z \) since the lattice \( L(E) \) is discrete, proving the first claim.

The second claim is proved similarly. Namely, if \( \varepsilon K \cap \overline{C}_\alpha \neq \emptyset \) with \( K \) compact, then \( \varepsilon K \cap \overline{C}_\alpha \neq \emptyset \). As \( \varepsilon K \cap \overline{C}_\alpha \subset \Gamma := \ker(N) \cap \overline{C}_\alpha \), we need to bound the number of \( \varepsilon \in E \) such that \( L(\varepsilon) + L(\varepsilon) \in L(\Gamma) \) for \( z \in K^\dagger \). But this is again bounded since \( K^\dagger \) is compact. \( \square \)

We can now prove that generic points \( z \in \mathbb{R}_+^{n} \times \mathbb{C}^{*r^2} \) satisfy the basic count formula (21) in Theorem 1. More precisely, let \( \partial \mathfrak{X}_\alpha := \mathfrak{X}_\alpha - \mathfrak{X}_\alpha \) be the boundary of \( \mathfrak{X}_\alpha \) and let

\[
(94) \quad B := \bigcup_{\alpha \in \mathfrak{X}_\alpha} (\mathfrak{X}_\alpha \times \mathbb{R}) \cup \bigcup_{\alpha \in \mathfrak{X}_\alpha} (\partial \mathfrak{X}_\alpha \times \mathbb{R}), \quad B := \bigcup_{\varepsilon \in E} \varepsilon f(B),
\]

where \( E := \langle \varepsilon_1, \ldots, \varepsilon_r \rangle \) and \( \mu_\alpha \) was defined in (10). Note that \( B \subset \mathbb{R}_+^{n} \times \mathbb{C}^{*r^2} \) is a subset of Lebesgue measure 0 since the cone \( \overline{C}_\alpha \) is degenerate if \( \mu_\alpha = 0 \).

We now prove the following claims.

(a) If \( \mu_\alpha \neq 0 \), then \( f \) maps \( \mathfrak{X}_\alpha \times \mathbb{R} \) bijectively onto the cone \( \overline{C}_\alpha \) in (77).

(b) The restriction of \( \hat{\pi} \) to \( \mathfrak{X} \times \mathbb{R} - B \) is a bijection onto \( \hat{T} - \hat{\pi}(B) \).

(c) \( F \) is surjective.

Because of (77), to prove (a) it suffices to show that \( f \) is injective on \( \mathfrak{X}_\alpha \times \mathbb{R} \). Let \( x = \sum_{i=1}^{n} c_i v_i \in \mathfrak{X}_\alpha \) with \( \sum_i c_i = 1 \) be the barycentric expansion of \( x \in \mathfrak{X}_\alpha \). Similarly, let \( x' = \sum_{i} c'_i v_i \in \mathfrak{X}_\alpha \) and suppose \( f(x \times y) = f(x' \times y') \). From (74) we find \( \varepsilon f(y) \sum_i c_i w_i = \varepsilon f(y') \sum_i c'_i w_i \). As we are assuming \( \mu_\alpha \neq 0 \), the \( w_i \) are linearly independent. Hence \( \varepsilon c_i = \varepsilon c'_i \) (0 \leq i \leq n - 1). Summing over \( i \) and using \( \sum_i c_i = 1 = \sum_i c'_i \) gives \( y = y' \) and \( c_i = c'_i \), proving claim (a).
Claim (b) follows since the quotient map $\mathbb{R}^{n-1} \to \mathbb{R}^{n-1}/\Lambda$ is surjective when restricted to $X$ and injective when restricted to $\bigcup_{\alpha \in \mathcal{A}} \hat{X}_\alpha$ (see Proposition 13 and (iv) in Definition 4). Claim (c) follows from Lemma 19 as $\deg(F) \neq 0$ implies the surjectivity of $F\mathcal{F}2$, Prop. 21 (3)).

Lemma 23. Let $z \in \mathbb{R}_{+}^n \times \mathbb{C}^{*r^2} - B$, where $B$ was defined in (10). Then

$$\sum_{\alpha \in \mathcal{A}} \mu_\alpha \sum_{\varepsilon(e) \in \mathcal{E}} 1 = 1,$$

where $\mu_\alpha = d_\alpha/\deg(F)$ was given in (10) using (95) and Lemma 15.

Proof. With the notation of (95), set $\gamma := \pi(z) \in T$ and suppose $\hat{x} \in F^{-1}(\gamma) \subset \hat{T}$. Such $\hat{x}$ exists since $F$ is surjective by (c) above. By (99), $\hat{x} = \hat{\pi}(x)$ for some $x \in X \times \mathbb{R}$. But

$$\pi(f(x)) = F(\hat{\pi}(x)) = F(\hat{x}) = \gamma = \pi(z),$$

shows that $f(x) = \varepsilon z$ for some $\varepsilon \in E$. As we assumed $z \notin B$, we have $x \notin B$. By (b) above, $\hat{x}$ uniquely determines $x$. Conversely, given $x \in X \times \mathbb{R}$ such that $f(x) = \varepsilon z$ for some $\varepsilon \in E$, then $\hat{x} := \hat{\pi}(x) \in F^{-1}(\gamma)$. As $f(x) \in \mathcal{C}_\alpha$ for some $\alpha \in \mathcal{A}$ with $\mu_\alpha \neq 0$, Lemma 24 and (a) above show that the set of such $\hat{x}$ is finite and that $F$ is a local homeomorphism in a neighborhood of $\hat{x}$. The local-global principle \cite{DF2} Prop. 21 (9)], Lemma 21 and (a) above give

$$\deg(F) = \deg_\alpha(F) = \sum_{x \in X \times \mathbb{R}} \text{locdeg}_x(F) = \sum_{x \in X \times \mathbb{R}} \text{locdeg}_{\pi(x)}(F)$$

$$= \sum_{\alpha \in \mathcal{A}} d_\alpha \sum_{x \in X \times \mathbb{R}} 1 = \sum_{\alpha \in \mathcal{A}} d_\alpha \sum_{\varepsilon \in E} 1. \quad \square$$

4.3. End of proof of Theorem 11. Having proved the basic count \cite{21} for generic $z$, we extend it to all $z \in \mathbb{R}_{+}^n \times \mathbb{C}^{*r^2}$ following Colmez’s unpublished idea for selecting boundary parts of the $\mathcal{C}_\alpha$’s. It is only here that we must finally assume that $k$ has at least one real embedding.

Lemma 24. Let $v_1, \ldots, v_l \in k \subseteq V := \mathbb{R}_{+}^n \times \mathbb{C}^{*r^2}$ be elements of $k$ with $\ell < n := [k : \mathbb{Q}]$, assume $r_1 \geq 1$, and define $e_1 \in V$ by $e_1^{(1)} = 1$ and $e_1^{(j)} = 0$ if $2 \leq j \leq r_1 + r_2$. Then $e_1$ is not contained in the real span of $v_1, \ldots, v_l$.

Proof. Following the proof in \cite{DF2} Lemma 9], define the $\mathbb{R}$-bilinear form on $V$,

$$\langle z, w \rangle := \sum_{j=1}^{r_1} z^{(j)} \overline{w}^{(j)} + 2 \sum_{j=r_1+1}^{r_1+r_2} \text{Re}(z^{(j)} \overline{w}^{(j)}) \quad (z, w \in V).$$

Note $\langle z, w \rangle = \text{Trace}_{k/\mathbb{Q}}(zw)$ for $z, w \in k$. As $\ell < n$, there exists $x \in k^*$ such that $\text{Trace}(xv_i) = 0$ for $1 \leq i \leq \ell$. Let $\psi : V \to \mathbb{R}$ be the $\mathbb{R}$-linear function $\psi(w) := \langle x, w \rangle$. Thus, $\psi(v_i) = 0$, and so $\psi(e_1) = 0$ if $e_1 \in \mathbb{R}v_1 + \ldots + \mathbb{R}v_l$. But (95) and $r_1 \neq 0$ give $x^{(1)} = (x, e_1) = \psi(e_1) = 0$, contradicting $x \in k^*$. \square

For any subset $C \subset V$ and $x, y \in V$, we shall say that $\hat{x}, \hat{y}$ pierces $C$ if $y \in C$ and the closed line segment $\hat{x}, \hat{y}$ connecting $x$ and $y$ intersects the interior of $C$. We now characterize piercing of a cone in terms of coordinates \cite{DF2} Lemma 14].
Lemma 25. Let \( w_0, \ldots, w_{n-1} \in V \) be a basis of a real vector space \( V \), let
\[
C = C(w_0, \ldots, w_{n-1}) := \{ t_0 w_0 + \cdots + t_{n-1} w_{n-1} \mid t_i \geq 0 \text{ for } 0 \leq i \leq n-1 \}
\]
be the corresponding closed polyhedral cone. In the basis \( w_0, \ldots, w_{n-1} \), write \( x = \sum_{j=0}^{n-1} x_j w_j \) and \( y = \sum_{j=0}^{n-1} y_j w_j \). Then
\[
\overline{x,y} \text{ pierces } C \iff [y_j \geq 0 \ (0 \leq j \leq n-1) \text{ and } [y_j = 0 \Rightarrow x_j > 0.]
\]
Furthermore, if \( \overline{x,y} \text{ pierces } C \) and \( s \in \overline{x,y} \) is an interior point of \( C \), then every point of \( s \overline{x,y} \) is an interior point of \( C \), except possibly for \( y \).

Proof. Suppose \( \overline{x,y} \text{ pierces } C \). Then \( y_j \geq 0 \) since \( y \in C \). Let \( s \in \overline{x,y} \) be in the interior of \( C \). Then \( s = (1-t)x + ty \) for some \( t \in [0,1] \) and \( s = \sum_j s_j w_j \) with \( s_j > 0 \ (0 \leq j \leq n-1) \). But \( s_j = (1-t)x_j + ty_j > 0 \ implies \ x_j > 0 \ whenever \ y_j = 0 \). Conversely, if \( y_j \geq 0 \), and \( y_j = 0 \Rightarrow x_j > 0 \), then for some sufficiently small positive \( \varepsilon \) and all \( t \in [1-\varepsilon,1) \), the point \( s := (1-t)x + ty \) lies in the interior of \( C \). To prove the last claim in the lemma, assume \( s_j > 0 \ (1 \leq j \leq n) \). Then \( (1-t)s + ty_j \geq (1-t)s_j > 0 \) if \( t \in [0,1] \). \( □ \)

Lemma 25 shows that an equivalent definition of the cone \( C_\alpha \) in (20) is
\[
C_\alpha = \{ y \in C_\alpha \mid \overline{e_1,y} \text{ pierces } C_\alpha \}
\]
This is useful because of the following “piercing invariance” of \( e_1 \).

Lemma 26. Assume \( r_1 > 0 \), let \( y \in V := \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \) and let \( \varepsilon \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \). Then \( \overline{e_1,y} \) pierces a closed polyhedral cone \( C = C(w_0, \ldots, w_{n-1}) \subset V \) if and only if \( \varepsilon e_1, \varepsilon y \) pierces \( C \).

Proof. We may assume that the \( n \) generators of \( C \) are \( \mathbb{R} \)-linearly independent, for otherwise there is no piercing at all and the lemma is trivial. As \( \varepsilon e_1 = \varepsilon^{(1)} e_1 \), where the real scalar \( \varepsilon^{(1)} > 0 \), the lemma follows from Lemma 25. \( □ \)

To complete the proof of Theorem 1 we will prove the basic count (21) in the form
\[
1 = \sum_{\alpha \in \mathcal{I}_r} \mu_\alpha \sum_{\varepsilon \in I_\alpha(y)} 1 = \sum_{\alpha \in \mathcal{I}_r} \mu_\alpha \text{Card}(I_\alpha(y)) \quad (y \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2}),
\]
where we have set
\[
I_\alpha(y) := \{ \varepsilon \in E \mid \varepsilon y \in C_\alpha \} = \{ \varepsilon \in E \mid \overline{e_1,\varepsilon y} \text{ pierces } C_\alpha \}.
\]
Note that Lemma 22 established (32) only for \( y \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} - \mathcal{B} \). If \( \mu_\alpha = 0 \) we have \( I_\alpha(y) = \emptyset \), for in this case \( C_\alpha \) has an empty interior. As in (15), Lemma 25, we will prove that the \( I_\alpha \) stabilize along the path from \( e_1 \) to \( y \).

Lemma 27. For \( t \in [0,1] \) and \( y \in \mathbb{R}^{r_1} \times \mathbb{C}^{r_2} \), parametrize the line-segment \( \overline{e_1,y} \) by \( P_y(t) := (1-t)e_1 + ty \). Then there exists \( T_0 = T_0(y) \in (0,1) \) such that \( I_\alpha(y) = I_\alpha(P_y(t)) \) for all \( \alpha \in \mathcal{I}_r \) and all \( t \in [T_0,1] \). Moreover, \( T_0 \) can be chosen so that \( P_y(t) \notin \mathcal{B} \) for all \( t \in [T_0,1] \).

Proof. Suppose \( \varepsilon \in I_\alpha(y) \) for some \( \alpha \in \mathcal{I}_r \), i.e. \( \overline{e_1,\varepsilon y} \) pierces \( C_\alpha \). By Lemma 22 \( \overline{e_1,\varepsilon y} \) pierces \( C_\alpha \). Thus, for some \( s = s(\alpha,\varepsilon) \in (0,1) \), the point \( (1-s)\varepsilon e_1 + sy \) is an interior point of \( C_\alpha \). By Lemma 22 \((1-t)\varepsilon e_1 + t\varepsilon y \) is also an interior point of
Lemma 24. If \( \mu \in R \) follows that \( \varepsilon \in y \) and \( \varepsilon \) belongs to a finite set. Passing to a subsequence we can assume that the \( \varepsilon \) converges to \( y \). We can now finish the proof of Theorem 1, i.e. the basic count for \( \varepsilon \in I_\alpha(y) \) for all \( y \in \mathbb{R}^n \) or \( \mathbb{C} \), as reformulated in (96). Using Lemma 27, we have \( I_\alpha(P_y(t)) = I_\alpha(y) \) and \( P_y(t) \notin B \) for some \( t \in (0, 1) \). Hence, by Lemma 28

\[
\sum_{\alpha \in \mathcal{J}} \mu_\alpha \sum_{\varepsilon \in I_\alpha(y)} 1 = \sum_{\alpha \in \mathcal{J}} \mu_\alpha \sum_{\varepsilon \in I_\alpha(P_y(t))} 1 = 1.
\]

References

[CDG] P. Charollois, S. Dasgupta and M. Greenberg, Integral Eisenstein cocycles on \( GL_n \), II: Shintani’s method, Comment. Math. Helvetici 90 (2015) 435–477.
[Co] P. Colmez, *Résidu en s = 1 des fonctions zêta p-adiques*, Invent. Math. 91 (1988) 371–389.

[DF1] F. Diaz y Díaz and E. Friedman, *Colmez cones for fundamental units of totally real cubic fields*, J. Number Th. 132 (2012), 1653–1663.

[DF2] F. Diaz y Díaz and E. Friedman, *Signed fundamental domains for totally real number fields*, Proc. London Math. Soc. 108 (2014), 965–988.

[Do] A. Dold, *Lectures on algebraic topology*, Grundlehren der mathematischen Wissenschaften 200, Berlin: Springer-Verlag (1972).

[Es] M. Espinoza, *Signed Shintani cones for number fields with one complex place*, J. Number Th. 145 (2014) 496–539.

[FR] E. Friedman and S. Ruijsenaars, *Shintani-Barnes zeta and gamma functions*, Adv. Math. 187 (2004) 362–395.

[Sh1] T. Shintani, *On evaluation of zeta functions of totally real algebraic number fields at non-positive integers*, J. Fac. Sci. Univ. Tokyo, Sec. IA 23 (1976) 393–417.

[Sh2] T. Shintani, *A remark on zeta functions of algebraic number fields*, in: *Automorphic Forms, Representation Theory and Arithmetic* (Bombay Colloquium, 1979), Berlin: Springer-Verlag (1981) 255–260.

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