

EULER-MACLAURIN FORMULAS VIA DIFFERENTIAL OPERATORS

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ABSTRACT. Recently there has been a renewed interest in asymptotic Euler-MacLaurin formulas, because of their applications to spectral theory of differential operators. Using elementary means, we recover such formulas for compactly supported smooth functions on intervals, polygons, and three-dimensional polytopes, where the coefficients in the asymptotic expansion are sums of differential operators involving only derivatives of the function in directions normal to the faces of the polytope. Our formulas apply to wedges of any dimension.

1. INTRODUCTION

Let Δ be a polytope in \mathbb{R}^n . Euler-MacLaurin formulas are expressions which may be used to approximate Riemann sums of smooth functions $f: \mathbb{R}^n \rightarrow \mathbb{R}$ such as

$$(1) \quad \frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap N\Delta} f\left(\frac{k}{N}\right),$$

in terms of integrals involving f and its derivatives. Such formulas may be traced back to the work of L. Euler and C. MacLaurin in the first half of the eighteenth century. This topic has attracted recent interest, see for instance the articles by Tate [Ta10], and Vergne [Ve13]. Our interest originates in the applications Euler-MacLaurin formulas have to spectral theory of differential operators as for instance in [Ze09].

An n -dimensional polytope $\Delta \subset \mathbb{R}^n$ is *simple* if there are exactly n edges meeting at each vertex of Δ ; it is *regular* if the primitive vectors in the direction of the edges span a basis of \mathbb{Z}^n , i.e. for each vertex v of Δ , the edges of Δ which intersect at v lie on rays $v + tw_i$, $0 \leq t < \infty$, where (w_1, \dots, w_n) is a lattice basis of \mathbb{Z}^n . A *Delzant polytope* is a simple and regular polytope. Recently, Tate [Ta10] obtained concrete Euler-MacLaurin formulas to approximate Riemann sums of the form (1) for smooth functions on lattice polytopes in any dimension, building primarily on the work of Berline and Vergne [BeVe07]. As a consequence of this general result, Tate obtained an explicit formula for Riemann sums over Delzant polytopes, that

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is Delzant polytopes in dimension two. The case of Delzant polygons is already of interest because such these arise as images of the moment maps of four-dimensional toric manifolds.

Let us briefly explain how toric manifolds enter the picture. Let (M, ω) be a compact connected symplectic toric manifold, let $\mu : M \rightarrow \mathbb{R}^n$ be the underlying moment map, and $\Delta = \mu(M)$ the associated Delzant polytope. Assume that there exists a prequantum line bundle $L \rightarrow M$, that is a holomorphic, Hermitian line bundle whose Chern connection has curvature $-i\omega$, and consider the space $\mathcal{H}_k = H^0(M, L^{\otimes k})$ of holomorphic sections of $L^{\otimes k}$; \mathcal{H}_k is the Hilbert space of geometric quantization. A standard result states that the dimension of \mathcal{H}_k is equal to the number $\#(\mathbb{Z}^n \cap (k\Delta/(2\pi)))$ of integer points in the polytope $k\Delta/(2\pi)$ (see [Ham08] for an exposition in the case $k = 1$, with a different convention which explains some differences by factors 2π), that is the so-called Ehrhart polynomial [Ehr62] of this polytope. An analogous result for toric varieties was one of the motivations behind work by Khovanskiĭ [Khov77, Khov78], followed by Khovanskiĭ and Pukhlikov [KhovPuk92a, KhovPuk92b], providing formulas for sums of values of f on lattice points of a lattice polytope, where f is the product of a polynomial and an exponential function.

More generally, let $(T_{1,k}, \dots, T_{n,k})$ be commuting self-adjoint Berezin-Toeplitz operators (each $T_{i,k}$ acts on the space \mathcal{H}_k defined above; for more details, see for instance [Schli10] and references therein) whose principal symbols are the components of the moment map $\mu : M \rightarrow \mathbb{R}^n$. A result recently obtained by Charles, Pelayo and Vũ Ngọc [ChPeVN2013, Theorem 1.11] states that the joint spectrum \mathcal{JS} (consisting of joint eigenvalues) of $T_{1,k}, \dots, T_{n,k}$ coincides, up to $\mathcal{O}(k^{-\infty})$, with the set

$$g\left(\Delta \cap \left(v + \frac{2\pi}{k}\mathbb{Z}^n\right), k\right),$$

where v is any vertex of the Delzant polytope $\Delta = \mu(M)$ and the sequence of functions $g(\cdot, k) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ admits a \mathcal{C}^∞ -asymptotic expansion of the form $g(\cdot, k) = \text{Id} + k^{-1}g_1 + k^{-2}g_2 + \dots$, where each $g_j : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is smooth. Thus, given any smooth function $F : \mathbb{R}^n \rightarrow \mathbb{R}$, the trace of the operator $F(T_{1,k}, \dots, T_{n,k})$ is equal to

$$\sum_{\lambda \in \mathcal{JS}} F(\lambda) = \sum_{x \in \mathbb{Z}^n \cap k\Delta/(2\pi)} \varphi\left(\frac{x}{k}\right) + \mathcal{O}(k^{-\infty}),$$

where $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}$ is defined by the formula $\varphi(x) = F(g(v + 2\pi x))$; the particular case $F = 1$ corresponds to the computation of the dimension of \mathcal{H}_k , see the discussion above. The right-hand side of this equality is of the form (1), up to a multiplicative factor k^n , and can thus be evaluated thanks to Euler-MacLaurin formulas.

The goal of this paper is double. Firstly, we recover some of Tate's results by elementary methods—different from those used in [Ta10]—starting from a result due to Guillemin and Sternberg [GuSt07], which was itself derived

by elementary means. Secondly, we provide explicit examples in dimension two. The structure of the paper is as follows: in Section 2 we will state our main result, and the remaining sections of the paper are devoted to its proof and further refinements. In the case of polygons, our approach leads to formulas in which the coefficients in the asymptotic expansion can be explicitly calculated, and we do so in Section 7.

2. MAIN RESULT

Let $n \geq 1$ and let \mathbb{Z}^n be the integer lattice in \mathbb{R}^n . Let $(\mathbb{Z}^n)^*$ and $(\mathbb{R}^n)^*$ be the corresponding dual spaces. Let $\langle \cdot, \cdot \rangle$ denote the pairing of $(\mathbb{R}^n)^*$ with \mathbb{R}^n . The subset $W \subset \mathbb{R}^n$ defined by the inequalities

$$(2) \quad \langle u_i, x \rangle \leq c_i, \quad i \in \{1, \dots, m\}$$

is called an *integer m -wedge* if for every $i \in \{1, \dots, m\}$ the constant c_i is an integer and the vector u_i is a primitive lattice vector in $(\mathbb{R}^n)^*$. Let U be the subspace of $(\mathbb{R}^n)^*$ spanned by the u_i 's. We say that W is *regular* if $\{u_1, \dots, u_m\}$ is a lattice basis of the lattice $U \cap (\mathbb{Z}^n)^*$.

When $m = n$, define the diffeomorphism $\varphi \in \mathcal{C}^\infty(\mathbb{R}^n, \mathbb{R}^n)$ such that $\varphi(x) = y$ has coordinates $y_i := \langle u_i, x \rangle - c_i$, $i \in \{1, \dots, n\}$, in the standard orthonormal basis of \mathbb{R}^n . Let \mathcal{H}_i be the facet of W defined by

$$\mathcal{H}_i := \{x \in W \mid \langle u_i, x \rangle = c_i\}.$$

For $\alpha = (\alpha_i)_{1 \leq i \leq n} \in \mathbb{N}^n$, set

$$F := \bigcap_{i, \alpha_i > 0} \mathcal{H}_i,$$

let the constant $K_\alpha(W)$ be defined as the Jacobian of the diffeomorphism $\varphi|_F : F \rightarrow \bigcap_{i, \alpha_i > 0} \{y_i = 0\}$, and write

$$\int_F^* := K_\alpha(W) \int_F.$$

Let $(v_i)_{1 \leq i \leq n}$ be the dual basis of $(u_i)_{1 \leq i \leq n}$. The constant $K_\alpha(W)$ is the inverse of the volume of the parallelotope generated by the vectors v_i for those i that satisfy $\alpha_i = 0$, that is, the primitive outwards vectors defining the face F (see Figure 1).

We introduce the following notation:

- $\alpha! = \alpha_1! \dots \alpha_n!$,
- $r(\alpha) \in \mathbb{N}^n$ is given by $r(\alpha)_i = 1$ if $\alpha_i > 0$, $r(\alpha)_i = 0$ if $\alpha_i = 0$,
- if $u_1, \dots, u_n \in \mathbb{R}^n$, u_α is the $|\alpha|$ -tuple of vectors

$$u_\alpha = \underbrace{(u_1, \dots, u_1)}_{\alpha_1 \text{ times}}, \dots, \underbrace{(u_n, \dots, u_n)}_{\alpha_n \text{ times}},$$

- $\nu(\alpha)$ stands for the number of indices i such that $\alpha_i > 0$.

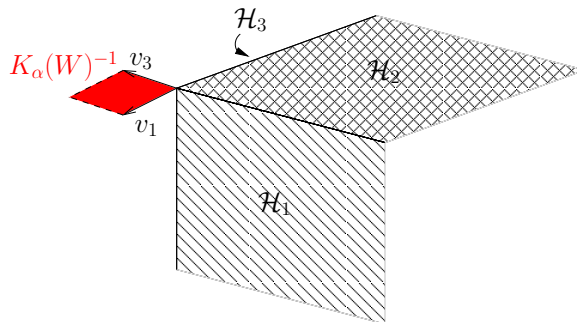


FIGURE 1. Computation of $K_\alpha(W)$; here $\alpha = (0, 1, 0)$.

We define b_n , $n \geq 0$ as follows: $b_0 = 1$, $b_1 = 1/2$, $b_{2p+1} = 0$ if $p \geq 1$ and $b_{2p} = (-1)^{p-1} B_p$, with B_p the p -th Bernoulli number. Let

$$C(W, \alpha) := \lambda_\alpha K_\alpha(W),$$

where, for $\alpha \in \mathbb{N}^n$,

$$\lambda_\alpha = \frac{1}{\alpha!} \prod_{i=1}^n b_{\alpha_i}.$$

A regular n -wedge is an example of an n -dimensional Delzant polytope. Let $\Delta \subset \mathbb{R}^n$ be an n -dimensional polytope, and suppose that Δ has d facets. Then Δ is defined by d equations: $\langle u_i, x \rangle \leq c_i$, where $i \in \{1, \dots, d\}$. For $q \in \llbracket 1, n \rrbracket$, we denote by \mathcal{F}_q the set of faces of codimension q of Δ .

The following theorem gives asymptotic Euler-MacLaurin formulas for Riemann sums. It holds in any dimension for wedges, and in dimensions one, two, and three for polytopes. The case of four-dimensional polytopes is more complicated to handle with our techniques, and we leave it to future work (see Remark 5.5). The first assertion of the theorem is similar to [Ta10, Proposition 3.1], and the second one is similar to [Ta10, Theorem 5.1]. In fact, the uniqueness result [Ta10, Theorem 5.3] implies that the operators that we construct are the same, but what differs is the way in which we obtain them.

Theorem 2.1. *Let $f \in \mathcal{C}_0^\infty(\mathbb{R}^n)$. Then the following hold.*

(i) *If W is a regular n -dimensional wedge in \mathbb{R}^n ,*

$$\frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap NW} f\left(\frac{k}{N}\right) \sim \sum_{q \geq 0} N^{-q} \sum_{\substack{\alpha \in \mathbb{N}^n \\ |\alpha| = q}} C(W, \alpha) \int_{\bigcap_{\substack{1 \leq i \leq n \\ \alpha_i > 0}} \mathcal{H}_i} D^{q-\nu(\alpha)} f \cdot v_{\alpha-r(\alpha)},$$

where the integral is taken over W if the intersection is empty, and the integral over a single point means evaluation at this point. The sign \sim indicates equality modulo $\mathcal{O}(N^{-\infty})$, i.e. that the difference between both sides is $\mathcal{O}(N^{-k})$ for every $k \geq 0$.

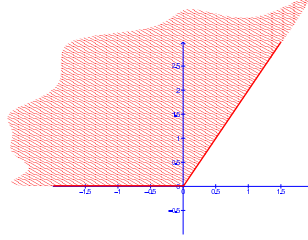


FIGURE 2. A two-dimensional wedge.

- (ii) If $\Delta \subset \mathbb{R}^n$, $n \in \{1, 2, 3\}$, is an n -dimensional Delzant polytope with vertices in \mathbb{Z}^n , for every $q \geq 1$ and every face $F \in \mathcal{F}_m$ with $m \leq q$, there exists a linear differential operator $R_q(F, \cdot)$ of degree $q - m$, depending only on F and involving only derivatives of f in directions normal to F , such that

$$\frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap N\Delta} f\left(\frac{k}{N}\right) \sim \int_{\Delta} f + \sum_{q \geq 1} N^{-q} \sum_{\substack{1 \leq m \leq q \\ F \in \mathcal{F}_m}} \int^* R_q(F, f).$$

Theorem 2.1 will follow from combining several upcoming results, namely Proposition 4.1, Theorem 5.4 and Theorem 6.1. Some of the results of the paper are more general than Theorem 2.1, but we leave them to later sections for simplicity. Our proof of Theorem 2.1 is different from the proof of Tate's general result in [Ta10, Theorem 5.1], elementary (in the sense that it relies only on freshman calculus), and self-contained, except for results due to Guillemin and Sternberg that we state in the next section, which can themselves be derived by elementary methods. We expect to extend part (ii) of Theorem 2.1 to higher dimensions in future work. In the case where Δ is a polygon, we give concrete expressions for the coefficients in the second formula in Theorem 2.1, see Theorem 7.2.

3. GUILLEMIN-STERNBERG FORMULAS FOR REGULAR WEDGES AND DELZANT POLYTOPES

3.1. Formula for regular wedges. The following approximation result was recently proven by Guillemin and Sternberg [GuSt07].

Lemma 3.1. *Let W be a regular integer m -wedge defined by the inequalities (2). For $h = (h_1, \dots, h_m) \in \mathbb{R}^n$, let W_h be the perturbed set defined by $\langle u_i, x \rangle \leq c_i + h_i$, $i \in \{1, \dots, m\}$. Then, if $f \in \mathcal{C}_0^\infty(\mathbb{R}^n)$, we have that*

$$\frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap NW} f\left(\frac{k}{N}\right) \sim \left(\tau\left(\frac{1}{N} \frac{\partial}{\partial h}\right) \int_{W_h} f(x) dx \right) (h=0),$$

where $\tau(s_1, \dots, s_m) = \tau(s_1) \dots \tau(s_m)$ and

$$\tau(s) = \frac{s}{1 - \exp(-s)}$$

is the Todd function.

3.2. Formula for Delzant polytopes. Now let $\Delta \subset \mathbb{R}^n$ be an n -dimensional Delzant polytope with vertices in \mathbb{Z}^n and exactly d facets. Then Δ is defined by the inequalities $\langle u^i, x \rangle \leq c_i$, $i \in \{1, \dots, d\}$ where c_i is an integer and $u^i \in (\mathbb{Z}^n)^*$ is a primitive vector perpendicular to the i^{th} -facet of Δ , and pointing outwards from Δ .

Because Δ is simple by assumption, every codimension k face of Δ is defined by a collection of equalities $\langle u^i, x \rangle = c_i$, $i \in F$, where F is a subset with k elements of the set $\{1, \dots, d\}$. Let W_F denote the k -wedge defined by the inequalities $\langle u^i, x \rangle \leq c_i$, $i \in F$. Because Δ is regular, each k -wedge W_F is regular. Guillemin and Sternberg have recently shown [GuSt07] the following Euler-MacLaurin formula.

Theorem 3.2. *Let Δ_h be the perturbed polytope defined by the equations $\langle u^i, x \rangle \leq c_i + h_i$, $i \in \{1, \dots, d\}$. Then, if $f \in \mathcal{C}_0^\infty(\mathbb{R}^n)$, we have*

$$\frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap N\Delta} f\left(\frac{k}{N}\right) \sim \left(\tau\left(\frac{1}{N} \frac{\partial}{\partial h}\right) \int_{\Delta_h} f(x) dx \right) (h=0),$$

where

$$\tau(s_1, \dots, s_d) = \tau(s_1) \dots \tau(s_d)$$

and $\tau(s_i)$ is the Todd function on the variable s_i , for every $i \in \{1, \dots, d\}$.

Remark 3.3. A general asymptotic Euler-MacLaurin formula for Riemann sums over lattice polytopes (simple or not) was given by Tate [Ta10]. As far as we know, Theorem 3.2 does not follow from Tate's formula. \circlearrowright

4. ASYMPTOTIC EXPANSION FOR REGULAR WEDGES

Let W be a regular integer n -wedge defined by the inequalities (2). Recall that $(v_i)_{1 \leq i \leq n}$ is the dual basis of $(u_i)_{1 \leq i \leq n}$ and \mathcal{H}_i is the facet of W defined by

$$\mathcal{H}_i = \{x \in W \mid \langle u_i, x \rangle = c_i\}.$$

Thus v_i generates the edge $\bigcap_{j \neq i} \mathcal{H}_j$. For any integer q , we introduce the operator $T_q(W, \cdot)$ defined by the formula

$$T_q(W, f) = \sum_{\substack{\alpha \in \mathbb{N}^n \\ |\alpha| = q}} \lambda_\alpha K_\alpha(W) \int_{\bigcap_{i, \alpha_i > 0} \mathcal{H}_i} D^{q-\nu(\alpha)} f \cdot v_{\alpha-r(\alpha)}$$

with the convention that the integral is taken over W if the intersection is empty, and that integrating a function over a vertex means evaluating it at this vertex. $K_\alpha(W)$ is a constant depending only on the face $\bigcap_{i, \alpha_i > 0} \mathcal{H}_i$, of which we gave an interpretation earlier.

Proposition 4.1. *If $f \in \mathcal{C}_0^\infty(\mathbb{R}^n)$, we have that*

$$(3) \quad \frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap NW} f\left(\frac{k}{N}\right) \sim \sum_{q \geq 0} N^{-q} T_q(W, f).$$

Proof. The idea of the proof is the following: firstly, we compute the full asymptotic expansion given by Lemma 3.1 in the case of the standard n -wedge $\{x \in \mathbb{R}^n; x_1 \leq 0, \dots, x_n \leq 0\}$. Then, we perform a change of variables to deal with the case of a general regular n -wedge.

We start by writing the expansion of $\tau(s_1, \dots, s_n) = \tau(s_1) \dots \tau(s_n)$; we recall that

$$\tau(s) = \frac{s}{1 - \exp(-s)} = \sum_{n=0}^{+\infty} b_n \frac{s^n}{n!}.$$

Using the numbers λ_α defined earlier, write

$$\tau(s_1, \dots, s_n) = \sum_{\alpha \in \mathbb{N}^n} \lambda_\alpha s^\alpha,$$

where $s^\alpha = s_1^{\alpha_1} \dots s_n^{\alpha_n}$. The coefficient S_q of N^{-q} in $\tau\left(\frac{\partial}{\partial h}\right)$ is equal to

$$\sum_{\alpha \in \mathbb{N}^n, |\alpha|=q} \lambda_\alpha \frac{\partial^\alpha}{\partial h^\alpha}$$

with

$$\frac{\partial^\alpha}{\partial h^\alpha} = \frac{\partial^{\alpha_1}}{\partial h_1^{\alpha_1}} \dots \frac{\partial^{\alpha_n}}{\partial h_n^{\alpha_n}}.$$

Hence

$$S_q = \sum_{\alpha \in \mathbb{N}^n, |\alpha|=q} \lambda_\alpha \frac{\partial^\alpha}{\partial h^\alpha}.$$

From this result, we deduce a formula for the case of the standard wedge. Remember that

$$\int_{W_h} f(x) dx = \int_{-\infty}^{h_1} \dots \int_{-\infty}^{h_n} f(x_1, \dots, x_n) dx_1 \dots dx_n;$$

thus we have that

$$\left(\frac{\partial}{\partial h_i} \int_{W_h} f(x) dx \right) \Big|_{h=0} = \int_{-\infty}^0 \dots \int_{-\infty}^0 f(\widehat{x}_i) \widehat{dx}_i = \int_{\{x_i=0\}} f$$

where $\widehat{x}_i = (x_1, \dots, x_{i-1}, 0, x_{i+1}, \dots, x_n)$ and $\widehat{dx}_i = dx_1 \dots dx_{i-1} dx_{i+1} \dots dx_n$. From this we obtain the following formula when $\alpha_i \geq 1$:

$$\left(\frac{\partial^{\alpha_i}}{\partial h_i^{\alpha_i}} \int_{W_h} f(x) dx \right) \Big|_{h=0} = \int_{\{x_i=0\}} \frac{\partial^{\alpha_i-1} f}{\partial x_i^{\alpha_i-1}}.$$

This finally yields

$$(4) \quad \frac{\partial^\alpha}{\partial h^\alpha} \int_{W_h} f(x) dx = \int_{\bigcap_{i, \alpha_i > 0} \{x_i = 0\}} \frac{\partial^{\alpha-r(\alpha)} f}{\partial x^{\alpha-r(\alpha)}}.$$

This gives the desired formula in the case of the standard wedge.

Let us now turn to the general case. Let W be the regular n -wedge defined by the inequalities (2). As before, define the diffeomorphism $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}^n$, such that $\varphi(x) = y$ has the following coordinates in the standard orthonormal basis of \mathbb{R}^n :

$$\forall i \in \{1, \dots, n\} \quad y_i = \langle u_i, x \rangle - c_i.$$

Then $\varphi(W)$ is the standard wedge; moreover, φ is a diffeomorphism from $\bigcap_{i \in I} \mathcal{H}_i$ to $\bigcap_{i \in I} \{x_i = 0\}$ for each subset I of $\llbracket 1, n \rrbracket$. We have that

$$\sum_{k \in \mathbb{Z}^n \cap NW} f\left(\frac{k}{N}\right) = \sum_{\ell \in \varphi(\mathbb{Z}^n) \cap N\varphi(W)} g\left(\frac{\ell}{N}\right) \stackrel{c_i \text{ integers}}{=} \sum_{\ell \in \mathbb{Z}^n \cap N\varphi(W)} g\left(\frac{\ell}{N}\right)$$

with $g = f \circ \varphi^{-1}$. But we know from the previous case that

$$\sum_{\ell \in \mathbb{Z}^n \cap N\varphi(W)} g\left(\frac{\ell}{N}\right) \sim \sum_{q \geq 0} N^{-q} T_q(\varphi(W), g);$$

therefore, it only remains to prove that for every $q \geq 0$, the equality $T_q(\varphi(W), g) = T_q(W, f)$ holds. We express the quantity $\frac{\partial^m g}{\partial y_i^m}$ in terms of f . Since $g = f \circ \varphi^{-1}$, we have

$$\frac{\partial g}{\partial y_i}(y) = Df(\varphi^{-1}(y)) \cdot D_{y_i}(\varphi^{-1})(y);$$

but $D_{y_i}(\varphi^{-1})(y) = v_i$ since

$$\varphi^{-1}(y) = \sum_{j=1}^n (y_j + c_j) v_j.$$

It follows that

$$\frac{\partial g}{\partial y_i}(y) = Df(\varphi^{-1}(y)) \cdot v_i.$$

By induction, we find that

$$\frac{\partial^m g}{\partial y_i^m}(y) = D^m f(\varphi^{-1}(y)) \cdot (v_i, \dots, v_i).$$

Now, we have to understand integrals of the form

$$I = \int_{\bigcap_{i, \alpha_i > 0} \{y_i = 0\}} \frac{\partial^{\alpha-r(\alpha)} g}{\partial y^{\alpha-r(\alpha)}}.$$

From the previous discussion, we obtain

$$I = \int_{\varphi(\cap_{i,\alpha_i>0} \mathcal{H}_i)} D^{|\alpha-r(\alpha)|} f(\varphi^{-1}(y)) \cdot v_{\alpha-r(\alpha)}.$$

Hence

$$I = K_\alpha(W) \int_{\cap_{i,\alpha_i>0} \mathcal{H}_i} D^{q-\nu(\alpha)} f \cdot v_{\alpha-r(\alpha)}$$

where $K_\alpha(W)$ is the Jacobian of the diffeomorphism $\varphi|_{\cap_{i,\alpha_i>0} \mathcal{H}_i}$, which was to be proved. \square

5. EXPLICIT ASYMPTOTIC EXPANSION FOR REGULAR WEDGES

In order to deduce a formula for polygons and three-dimensional polytopes, we rewrite the asymptotic expansion in Proposition 4.1 in a suitable form. Some of the results of this section apply for general $n \geq 1$. The final results require that $n = 1, 2$, or 3 .

5.1. General results. Recall that for $d \in \llbracket 1, n \rrbracket$, \mathcal{F}_d denotes the set of faces of codimension d of W . Our objective is to write a formula of the kind:

$$T_q(W, f) = \sum_{d=0}^{n-1} \sum_{F \in \mathcal{F}_d} S_q(F, f)$$

where $S_q(F, \cdot)$ is a differential operator associated with the face F , with good properties in a sense that we will precise later. Let $F \in \mathcal{F}_d$. There exists a subset $I = \{i_1, \dots, i_d\}$ of $\llbracket 1, n \rrbracket$ such that $F = \cap_{j \in I} \mathcal{H}_j$; the family $(v_i)_{i \notin I}$ is a basis of the linear subspace spanned by F . A first expression for $S_q(F, f)$ is

$$S_q(F, f) = \sum_{\substack{\alpha \in \mathbb{N}^n, |\alpha|=q \\ \{i, \alpha_i > 0\} = I}} \lambda_\alpha \int_F^* D^{q-d} f \cdot v_{\alpha-r(\alpha)}.$$

Observe that if $d > q$, then $S_q(F, f) = 0$. If $d = q$, then $S_q(F, f)$ only involves the integral $\int_F^* f$. When $d < q$, the situation is a little bit more complicated, because we integrate directional derivatives of f involving the vectors $v_i, i \in I$. But we would like to keep only quantities that depend on the face F and nothing else; this is why we decompose the vectors $v_i, i \in I$ as follows:

$$(5) \quad v_i = \sum_{j \notin I} \mu_{ij}^F v_j + \sum_{j \in I} \zeta_{ij}^F n_j$$

where n_j is the outward primitive normal to the facet \mathcal{H}_j . Next, we expand the quantity $D^{q-d} f \cdot v_{\alpha-r(\alpha)}$ as a linear combination of n^{q-d} terms involving the vectors $v_j, j \notin I$ and $n_j, j \in I$.

More precisely, write equation (5) as

$$v_i = \sum_{j=1}^n \lambda_{ij}^F w_j$$

where $\lambda_{ij}^F = \mu_{ij}^F$, $w_j = v_j$ if $j \notin I$ and $\lambda_{ij}^F = \zeta_{ij}^F$, $w_j = n_j$ if $j \in I$. Moreover, set $\beta = \alpha - r(\alpha)$ and define integers k_ℓ , $1 \leq \ell \leq q-d$ as follows: $k_\ell = i_1$ if $1 \leq \ell \leq \beta_{i_1}$, \dots , $k_\ell = i_d$ if $q-d - \beta_{i_d} \leq \ell \leq q-d$. Then

$$D^{q-d} f \cdot v_{\alpha-r(\alpha)} = D^{q-d} f \cdot \left(\sum_{j_1=1}^n \lambda_{k_1 j_1}^F w_{j_1}, \dots, \sum_{j_{q-d}=1}^n \lambda_{k_{q-d} j_{q-d}}^F w_{j_{q-d}} \right)$$

which can be written by multilinearity as

$$D^{q-d} f \cdot v_{\alpha-r(\alpha)} = \sum_{j_1, \dots, j_{q-d}=1}^n \left(\prod_{\ell=1}^{q-d} \lambda_{k_\ell j_\ell}^F \right) D^{q-d} f \cdot (w_{j_1}, \dots, w_{j_{q-d}}).$$

We now want to eliminate the vectors v_j , $j \notin I$ when they appear in the quantity

$$D^{q-d} f \cdot (w_{j_1}, \dots, w_{j_{q-d}}).$$

If j_1, \dots, j_{q-d} all belong to I , then only the normal vectors n_j appear, and we have nothing to do; this constitutes d^{q-d} favorable cases. In order to handle the unfavorable cases, we will use the following lemma.

Lemma 5.1. *For any function $g \in \mathcal{C}_0^\infty(\mathbb{R}^n)$ and for every $j \notin I$, we have*

$$\int_F^* Dg \cdot v_j = \int_{F_j}^* g$$

where F_j is the face of codimension $d+1$ defined by $F_j = F \cap \mathcal{H}_j$.

Proof. Let the elements of $\llbracket 1, n \rrbracket \setminus I$ be denoted by $x_j, x_{i_{d+2}}, \dots, x_{i_n}$. One has

$$\begin{aligned} \int_F^* Dg \cdot v_j &= \int_{\{x_{i_1}=\dots=x_{i_d}=0\}} Dg(\varphi^{-1}(x)) \cdot v_j \, dx_j dx_{i_{d+2}} \dots dx_{i_n} \\ &= \int_{\{x_{i_1}=\dots=x_{i_d}=0\}} Dg(\varphi^{-1}(x)) \cdot D_{x_j}(\varphi^{-1})(x) \, dx_j dx_{i_{d+2}} \dots dx_{i_n} \\ &= \int_{\{x_{i_1}=\dots=x_{i_d}=0\}} \frac{\partial}{\partial x_j} (g \circ \varphi^{-1})(x) \, dx_j dx_{i_{d+2}} \dots dx_{i_n} \\ &= \int_{\{x_{i_1}=\dots=x_{i_d}=x_j=0\}} (g \circ \varphi^{-1})(x) \, dx_{i_{d+2}} \dots dx_{i_n} = \int_{F_j}^* g. \end{aligned}$$

□

5.2. Results for regular two and three-dimensional wedges. When $n = 1, 2, 3$, by applying Lemma 5.1 to functions of the form

$$g = D^{q-d-1}f,$$

and repeating this as many times as necessary, we eliminate all the vectors v_j , $j \notin I$ in the expression of

$$\int_F^* D^{q-d}f \cdot v_{\alpha-r(\alpha)},$$

and keep only integrals over faces of codimension greater than d of derivatives of f applied to vectors that are normal to the hyperplanes defining the faces.

Before we state and prove our result, let us introduce some notation. Let $C(W, F)$ be the cone generated by the set $\{x - y, y \in W, x \in F\}$. If X is a non-empty subset of \mathbb{R}^n , let $L(X)$ be the vector subspace generated by the elements of the form $y - x$, $x, y \in X$. The following two lemmas hold in any dimension (not just two and three).

Lemma 5.2. *Decompose the vectors v_i , $i \in I$, as in equation (5). Choose another set of vectors $(w_i)_{i \in I}$ such that*

- $\forall i \in I$, w_i belongs to

$$L\left(\bigcap_{j \in [1, n] \setminus \{i\}} \mathcal{H}_j\right) \cap C(W, F),$$

- the family $((v_j)_{j \notin I}, (w_j)_{j \in I})$ is a primitive lattice basis,

and write, for $i \in I$,

$$w_i = \sum_{j \notin I} \tilde{\mu}_{ij}^F v_j + \sum_{j \in I} \tilde{\zeta}_{ij}^F n_j.$$

Then for $j \in I$, we have $\tilde{\zeta}_{ij}^F = \zeta_{ij}^F$.

In other words, this means that the scalars ζ_{ij}^F only depend on the face F ; when F will be considered as a face of a polytope instead of a wedge, then the contribution coming from each wedge will display the same coefficient.

Proof. By definition of the vectors v_j , n_j , $1 \leq j \leq n$, one has

$$(6) \quad \forall \ell \in I \quad \langle v_i, n_\ell \rangle = \sum_{j \notin I} \zeta_{ij}^F \langle n_j, n_\ell \rangle.$$

Hence, the d coefficients ζ_{ij}^F , $j \in I$, are obtained by solving the linear system (6) of d equations. Now, we express the vector w_i in the basis $\mathcal{B} = (v_j)_{1 \leq j \leq n}$:

$$w_i = \sum_{j \notin I} \alpha_{ij} v_j + \sum_{j \in I} \beta_{ij} v_j.$$

Since the vector w_i belongs to $L(\bigcap_{j \in \llbracket 1, n \rrbracket \setminus \{i\}} \mathcal{H}_j)$, all the scalar products $\langle w_i, n_j \rangle$, $j \in I \setminus \{i\}$, vanish. This implies that for every $j \in I \setminus \{i\}$, $\beta_{ij} = 0$. Thus, the matrix M of change of basis from \mathcal{B} to

$$\mathcal{B}' = ((v_j)_{j \notin I}, (w_j)_{j \in I})$$

is of the form

$$M = \begin{pmatrix} I_{n-d} & A \\ 0 & B \end{pmatrix}$$

where $B = \text{diag}(\beta_{11}, \dots, \beta_{dd})$. Since \mathcal{B} and \mathcal{B}' are primitive lattice bases, we have $\det(M) = \pm 1$, and hence for every $i \in I$, $\beta_{ii} = \pm 1$. But both v_i and w_i belong to $C(W, F)$, so $\beta_{ii} = 1$. This yields that for $\ell \in I$, we have $\langle w_i, n_\ell \rangle = \langle v_i, n_\ell \rangle$. \square

Lemma 5.3. *Decompose the vectors v_i , $i \in I$, as in equation (5), and fix $j \notin I$. Set $J = I \cup \{j\}$, and choose another set of vectors $(w_i)_{i \in J}$ such that*

- $\forall i \in J$, w_i belongs to

$$L \left(\bigcap_{k \in \llbracket 1, n \rrbracket \setminus \{i\}} \mathcal{H}_k \right) \cap C(W, F),$$

- the family $((v_i)_{i \notin J}, (w_i)_{i \in J})$ is a primitive lattice basis.

and write, for $i \in I$,

$$w_i = \tilde{\mu}_{ij}^F w_j + \sum_{k \notin J} \tilde{\mu}_{ik}^F v_k + \sum_{k \in I} \tilde{\zeta}_{ik}^F n_k.$$

Then we have $\tilde{\mu}_{ij}^F = \mu_{ij}^F$.

In other words, the scalar μ_{ij}^F only depends on the face $F \cap \mathcal{H}_j$.

Proof. By definition of the vectors v_k , n_k , $1 \leq k \leq n$, one has

$$\forall k \notin I \quad \langle v_i, v_k \rangle = \sum_{\ell \notin I} \mu_{i\ell}^F \langle v_\ell, v_k \rangle,$$

which can be written in matrix form

$$(7) \quad A\nu = V$$

where V, ν are the column vectors given by

$$\forall \ell \notin I \quad V_\ell = \langle v_i, v_\ell \rangle, \quad \nu_\ell = \mu_{i\ell}^F$$

and A is the symmetric matrix whose generic coefficient is $A_{k,\ell} = \langle v_k, v_\ell \rangle$, $k, \ell \notin I$. Similarly, the constants $\tilde{\mu}_{i\ell}^F$ satisfy the system of equations

$$(E_k) \quad \forall k \notin J \quad \langle w_i, v_k \rangle = \tilde{\mu}_{ij}^F \langle w_j, v_k \rangle + \sum_{\ell \notin J} \tilde{\mu}_{i\ell}^F \langle v_\ell, v_k \rangle$$

and

$$(E_i) \quad \langle w_i, w_j \rangle = \tilde{\mu}_{ij}^F \|w_j\|^2 + \sum_{\ell \notin J} \tilde{\mu}_{i\ell}^F \langle v_\ell, w_j \rangle.$$

Thanks to the proof of the previous lemma, we know that there exists scalars $\alpha_{k\ell}$, $k \in J$, $\ell \notin J$ such that

$$\forall k \in J \quad w_k = v_k + \sum_{\ell \notin J} \alpha_{k\ell} v_\ell.$$

Hence we obtain

$$\langle w_i, w_j \rangle = \langle v_i, v_j \rangle + \sum_{\ell \notin J} \alpha_{j\ell} \langle v_i, v_\ell \rangle + \sum_{k \notin J} \alpha_{ik} \langle v_j, v_k \rangle + \sum_{k, \ell \notin J} \alpha_{ik} \alpha_{j\ell} \langle v_\ell, v_k \rangle$$

as well as

$$\forall k \notin J \quad \begin{cases} \langle w_i, v_k \rangle = \langle v_i, v_k \rangle + \sum_{\ell \notin J} \alpha_{i\ell} \langle v_\ell, v_k \rangle \\ \langle w_j, v_k \rangle = \langle v_j, v_k \rangle + \sum_{\ell \notin J} \alpha_{j\ell} \langle v_\ell, v_k \rangle \end{cases}$$

and

$$\|w_j\|^2 = \|v_j\|^2 + 2 \sum_{\ell \notin J} \alpha_{j\ell} \langle v_j, v_\ell \rangle + \sum_{k, \ell \notin J} \alpha_{j\ell} \alpha_{jk} \langle v_\ell, v_k \rangle.$$

Using these relations, equations (E_k) become

$$(E'_k) \quad \langle v_i, v_k \rangle + \sum_{\ell \notin J} \alpha_{i\ell} \langle v_\ell, v_k \rangle = \tilde{\mu}_{ij}^F \langle v_j, v_k \rangle + \sum_{\ell \notin J} (\tilde{\mu}_{i\ell}^F + \tilde{\mu}_{ij}^F \alpha_{j\ell}) \langle v_\ell, v_k \rangle$$

while equation (E_i) becomes

$$(E'_i) \quad \begin{aligned} & \langle v_i, v_j \rangle + \sum_{\ell \notin J} \alpha_{j\ell} \langle v_i, v_\ell \rangle + \sum_{k \notin J} \alpha_{ik} \langle v_j, v_k \rangle + \sum_{k, \ell \notin J} \alpha_{ik} \alpha_{j\ell} \langle v_\ell, v_k \rangle \\ &= \tilde{\mu}_{ij}^F \|v_j\|^2 + 2 \sum_{\ell \notin J} \tilde{\mu}_{ij}^F \alpha_{j\ell} \langle v_j, v_\ell \rangle + \sum_{k, \ell \notin J} \tilde{\mu}_{ij}^F \alpha_{j\ell} \alpha_{jk} \langle v_\ell, v_k \rangle \\ & \quad + \sum_{\ell \notin J} \tilde{\mu}_{i\ell}^F \langle v_\ell, v_j \rangle + \sum_{k, \ell \notin J} \tilde{\mu}_{i\ell}^F \alpha_{jk} \langle v_\ell, v_k \rangle. \end{aligned}$$

Considering the linear combination $(E'_i) - \sum_{k \notin J} \alpha_{jk} (E'_k)$, we replace equation (E'_i) by the new equation (we do not write the details of the computations)

$$\langle v_i, v_j \rangle + \sum_{k \notin J} \alpha_{ik} \langle v_j, v_k \rangle = \tilde{\mu}_{ij}^F \|v_j\|^2 + \sum_{\ell \notin J} (\tilde{\mu}_{i\ell}^F + \tilde{\mu}_{ij}^F \alpha_{j\ell}) \langle v_\ell, v_j \rangle.$$

Together with equations (E'_k) , this means that the coefficients $\tilde{\mu}_{i\ell}^F$ are solutions of the system

$$AU + V = A\tilde{\nu}$$

where A and V are as before, $\tilde{\nu}$ is defined as ν but with the coefficients $\tilde{\mu}_{i\ell}^F$ instead of $\mu_{i\ell}^F$, and U is the column vector whose entries are

$$U_j = 0, \quad \forall \ell \notin I, \quad U_\ell = \alpha_{i\ell} - \tilde{\mu}_{ij}^F \alpha_{j\ell}.$$

Comparing this with (7) yields $\nu = \tilde{\nu} - U$, and in particular $\mu_{ij}^F = \tilde{\mu}_{ij}^F$. \square

Theorem 5.4. *Assume that $n \in \{1, 2, 3\}$. For every $q \geq 1$ and every face $F \in \mathcal{F}_d$ with $d \leq q$, there exists a linear differential operator $R_q(F, \cdot)$ of degree $q - d$, depending only on F (in the sense introduced in the previous lemmas) and involving only derivatives of f in directions normal to the face F , such that*

$$(8) \quad T_q(W, f) = \sum_{d=0}^{n-1} \sum_{F \in \mathcal{F}_d} \int^* R_q(F, f).$$

Proof. To compute $R_q(F, \cdot)$, we apply the previous technique to faces of codimension smaller than d and gather their contribution as integrals over F . It follows from Lemma 5.2 and Lemma 5.3 that $R_q(F, \cdot)$ depends only on the face F ; let us briefly explain how.

If $n = 2$, we have to handle two types of faces: the two edges ($d = 1$) and the vertex ($d = 2$) of the wedge. There is not much to say about the case of the vertex. When we integrate over an edge, and we apply our technique, we will find

- constants of type μ in front of derivatives of f evaluated at the vertex, and there is nothing to prove,
- constants of type ζ in front of integrals of derivatives of f on F , and Lemma 5.2 ensures that it only depends on the face F .

If $n = 3$, we have three types of faces, namely planes ($d = 1$), edges ($d = 2$) and the vertex ($d = 3$). The difference with the previous case is that when we consider integrals over a plane, we obtain integrals over edges belonging to this plane, each one displaying a factor of type μ ; Lemma 5.3 ensures that it only depends on the given edge. \square

Remark 5.5.

- (1) In dimension 4 and higher, Lemma 5.2 and Lemma 5.3 are not enough to obtain a similar theorem. Indeed, consider the following situation: we take $n = 4$ and want to evaluate

$$I = \int_{\mathcal{H}_1}^* D^2 f \cdot (v_1, v_1).$$

We start by expanding

$$v_1 = \mu_{12}^{\mathcal{H}_1} v_2 + \mu_{13}^{\mathcal{H}_1} v_3 + \mu_{14}^{\mathcal{H}_1} v_4 + \zeta_{11}^{\mathcal{H}_1} n_1,$$

and we apply Lemma 5.1 to obtain

$$\begin{aligned} I &= \mu_{12}^{\mathcal{H}_1} \int_{\mathcal{H}_1 \cap \mathcal{H}_2}^* Df \cdot v_1 + \mu_{13}^{\mathcal{H}_1} \int_{\mathcal{H}_1 \cap \mathcal{H}_3}^* Df \cdot v_1 + \mu_{14}^{\mathcal{H}_1} \int_{\mathcal{H}_1 \cap \mathcal{H}_4}^* Df \cdot v_1 \\ &\quad + \zeta_{11}^{\mathcal{H}_1} \int_{\mathcal{H}_1}^* D^2 f \cdot (v_1, n_1). \end{aligned}$$

We have to apply the method one more time for each of these integrals. For instance, we put

$$K = \int_{\mathcal{H}_1 \cap \mathcal{H}_2}^* Df \cdot v_1$$

and to compute this integral, we write

$$v_1 = \mu_{13}^{\mathcal{H}_1 \cap \mathcal{H}_2} v_3 + \mu_{14}^{\mathcal{H}_1 \cap \mathcal{H}_2} v_4 + \zeta_{11}^{\mathcal{H}_1 \cap \mathcal{H}_2} n_1 + \zeta_{12}^{\mathcal{H}_1 \cap \mathcal{H}_2} n_2$$

which yields, again thanks to Lemma 5.1

$$\begin{aligned} K &= \mu_{13}^{\mathcal{H}_1 \cap \mathcal{H}_2} \int_{\mathcal{H}_1 \cap \mathcal{H}_2 \cap \mathcal{H}_3}^* f + \mu_{14}^{\mathcal{H}_1 \cap \mathcal{H}_2} \int_{\mathcal{H}_1 \cap \mathcal{H}_2 \cap \mathcal{H}_4}^* f \\ &\quad + \zeta_{11}^{\mathcal{H}_1 \cap \mathcal{H}_2} \int_{\mathcal{H}_1 \cap \mathcal{H}_2}^* Df \cdot n_1 + \zeta_{12}^{\mathcal{H}_1 \cap \mathcal{H}_2} \int_{\mathcal{H}_1 \cap \mathcal{H}_2}^* Df \cdot n_2 \end{aligned}$$

Hence, in the expression of I , we obtain the term

$$\mu_{12}^{\mathcal{H}_1} \mu_{13}^{\mathcal{H}_1 \cap \mathcal{H}_2} \int_{\mathcal{H}_1 \cap \mathcal{H}_2 \cap \mathcal{H}_3}^* f;$$

does the factor only depend on the face $\mathcal{H}_1 \cap \mathcal{H}_2 \cap \mathcal{H}_3$? We think that our previous lemmas are not enough to give an answer to this question.

- (2) In principle, one should be able to obtain explicit expressions for the operators $R_q(F, f)$, but this leads to computations involving a large number of constants. If we restrict ourselves to dimension two, we can be explicit, as we will see later.

◊

6. ASYMPTOTIC EXPANSION FOR POLYGONS AND THREE-DIMENSIONAL POLYTOPES

As in Section 1, let $\Delta \subset \mathbb{R}^n$ be a Delzant polytope with vertices in \mathbb{Z}^n in dimension $n \in \{1, 2, 3\}$, defined by the equations $\langle u^i, x \rangle \leq c_i$, $i \in \{1, \dots, d\}$. Recall that for $m \in \llbracket 1, n \rrbracket$, \mathcal{F}_m denotes the set of faces of codimension m of Δ .

We introduce as in Theorem 5.4 the operators $R_q(F, \cdot)$ associated with a face F of the polytope (remembering that these only depend on the face as part of the polytope). For any integer q , we define the operator $T_q(\Delta, \cdot)$ by

$$(9) \quad T_q(\Delta, f) = \sum_{m=0}^{n-1} \sum_{F \in \mathcal{F}_m} \int_F^* R_q(F, f).$$

Theorem 6.1. *If $f \in \mathcal{C}_0^\infty(\mathbb{R}^n)$, we have that*

$$\frac{1}{N^n} \sum_{k \in \mathbb{Z}^n \cap N\Delta} f\left(\frac{k}{N}\right) = \sum_{q \geq 0} N^{-q} T_q(\Delta, f).$$

Proof. Notice first that $\Delta = \bigcap_{i=1}^p W_i$ where p is the number of vertices of Δ and W_i is the regular wedge which is the intersection of the n facets \mathcal{H}_j^i , $1 \leq j \leq n$, intersecting at the vertex v_i . Cover Δ by open sets Ω_i , $1 \leq i \leq p$, such that Ω_i contains the vertex v_i and does not intersect any other facet than the \mathcal{H}_j^i , $1 \leq j \leq n$. Choose a partition of unity associated with this open covering and write $f = \sum_{i=1}^p f_i$ where $f_i \in \mathcal{C}_0^\infty(\mathbb{R}^n)$ has support included in Ω_i . Then

$$\sum_{k \in \mathbb{Z}^n \cap N\Delta} f\left(\frac{k}{N}\right) = \sum_{i=1}^p \sum_{k \in \mathbb{Z}^n \cap NW_i} f_i\left(\frac{k}{N}\right).$$

Now, from formula (3), we know that for $1 \leq i \leq p$

$$\sum_{k \in \mathbb{Z}^n \cap NW_i} f_i\left(\frac{k}{N}\right) \sim \sum_{\alpha \geq 0} N^{-\alpha} T_\alpha(W_i, f_i);$$

hence it is enough to check that for all q

$$\sum_{i=1}^p T_q(W_i, f_i) = T_q(\Delta, f).$$

This amounts to showing that for each face F of the polytope,

$$\sum_{i=1}^p R_q(F, f_i) = R_q(F, f).$$

But this is clear because $R_q(F, \cdot)$ is linear and because $\sum_{i=1}^p f_i = f$. \square

7. EXPLICIT FORMULA IN DIMENSION TWO

We compute explicitly the operators $R_q(\Delta, \cdot)$ in dimension two. Let Δ be a regular integer polygon defined by the inequalities (2). In this case, we only have two types of faces: vertices (codimension two) and edges (codimension one). Let E (respectively V) be the set of edges (respectively vertices) of Δ . If e belongs to E , let n_e be the associated outward primitive normal vector; if v belongs to V , let $(w_1(v), w_2(v))$ be the integral basis of \mathbb{Z} such that the two edges meeting at v are contained in the half-lines $v + \lambda w_i(v)$, $\lambda \geq 0$; we denote by e_i the edge generated by $w_i(v)$. Define the quantities

$$\eta_1(v) = \frac{\langle w_1(v), w_2(v) \rangle}{\|w_1(v)\|^2}, \quad \eta_2(v) = \frac{\langle w_1(v), w_2(v) \rangle}{\|w_2(v)\|^2}.$$

and $\mu(v) = \eta_1(v) + \eta_2(v)$.

Now, let e be an edge, and let $C(\Delta, e)$ be the cone generated by the set $\{x - y, y \in \Delta, x \in e\}$. Given a generator v_1 of $e \cap \mathbb{Z}^2$, there exists a vector

$v_2 \in C(\Delta, e) \cap \mathbb{Z}^2$ such that (v_1, v_2) is a primitive lattice basis of \mathbb{Z}^2 . The following result is a corollary of Lemma 5.2.

Corollary 7.1. *The quantity*

$$\zeta(e) = \frac{\langle v_2, n_e \rangle}{\|n_e\|^2}$$

does not depend on the choice of $v_2 \in C(\Delta, e) \cap \mathbb{Z}^2$.

The following theorem gives the desired explicit expression.

Theorem 7.2. *The operators $T_q(\Delta, \cdot)$ from Theorem 6.1 are given by:*

- $T_0(\Delta, f) = \int_{\Delta} f(x) dx;$
- $T_1(\Delta, f) = \frac{1}{2} \sum_{e \in E} \int_e^* f;$
- $T_2(\Delta, f) = \sum_{v \in V} \left(\frac{1}{4} + \frac{\mu(v)}{12} \right) f(v) - \frac{1}{12} \sum_{e \in E} \zeta(e) \int_e^* Df \cdot n_e;$
- *if $p > 1$, then*

$$T_{2p}(\Delta, f) = \sum_{e \in E} R_{2p}(e, f) + \sum_{v \in V} R_{2p}(v, f)$$

where

$$R_{2p}(e, f) = (-1)^{p-1} \frac{B_p}{(2p)!} \zeta(e)^{2p-1} \int_e^* D^{2p-1} f \cdot (n_e, \dots, n_e)$$

and $R_{2p}(v, f)$ is equal to

$$\begin{aligned} & (-1)^{p-2} \sum_{\substack{m+\ell=p \\ m, \ell \geq 1}} \frac{B_m B_\ell}{(2m)!(2\ell)!} D^{2p-2} f(v) \cdot \underbrace{(w_1(v), \dots, w_1(v))}_{2m-1 \text{ times}} \underbrace{(w_2(v), \dots, w_2(v))}_{2\ell-1 \text{ times}} \\ & + (-1)^{p-2} \frac{B_p}{(2p)!} \eta_1(v) \sum_{k=0}^{2p-2} \zeta(e_1)^k D^{2p-2} f \cdot \underbrace{(n_{e_1}, \dots, n_{e_1})}_{k \text{ times}} \underbrace{(w_2(v), \dots, w_2(v))}_{2p-2-k \text{ times}} \\ & + (-1)^{p-2} \frac{B_p}{(2p)!} \eta_2(v) \sum_{k=0}^{2p-2} \zeta(e_2)^k D^{2p-2} f \cdot \underbrace{(n_{e_2}, \dots, n_{e_2})}_{k \text{ times}} \underbrace{(w_1(v), \dots, w_1(v))}_{2p-2-k \text{ times}}; \end{aligned}$$

- *if $p > 1$, $T_{2p+1}(\Delta, f)$ is equal to*

$$\frac{(-1)^{p-1} B_p}{2(2p)!} \sum_{v \in V} (D^{2p-1} f(v) \cdot (w_1(v), \dots, w_1(v)) + D^{2p-1} f(v) \cdot (w_2(v), \dots, w_2(v))).$$

Remark 7.3. Theorem 7.2 recovers the formula in [Ta10, Corollary 5.4]. To compare the two formulas, one may notice that Tate does not separate the even and odd cases, and that in the odd case nearly every coefficient in his formula vanishes because of the properties of the Bernoulli numbers. \circ

Proof. We have to compute the operators $R_q(F, \cdot)$ as in Section 5; we start by the case $q = 2$. Let v be a vertex and let W be the wedge formed by this vertex and the two incident edges. Define the vectors $w_1(v), w_2(v)$ as before, and let e_1 (respectively e_2) be the edge generated by $w_1(v)$ (respectively $w_2(v)$). We have

$$T_2(W, f) = \frac{1}{4}f(v) - \frac{1}{12} \left(\int_{e_1}^* \mathrm{D}f \cdot w_2(v) + \int_{e_2}^* \mathrm{D}f \cdot w_1(v) \right)$$

If n_i is the outward primitive vector normal to the edge e_i , we write

$$w_i(v) = \alpha_i w_j(v) + \beta_i n_j$$

where $j = 2$ (respectively 1) if $i = 1$ (respectively 2). Taking the scalar product with n_j and $w_j(v)$, we find

$$\alpha_i = \frac{\langle w_i(v), w_j(v) \rangle}{\|w_j(v)\|^2} = \eta_j(v), \quad \beta_i = \frac{\langle w_i(v), n_j \rangle}{\|n_j\|^2} = \zeta(e_j).$$

Now, thanks to Lemma 5.1, we have (being careful that $w_i(v)$ is the opposite of the vector v_j in this lemma)

$$\int_{e_j}^* \mathrm{D}f \cdot w_i(v) = -\alpha_i f(v) + \zeta(e_j) \int_{e_j}^* \mathrm{D}f \cdot n_j.$$

Adding the contributions from each vertex, we obtain the desired formula.

Now, let $p > 1$; then

$$\begin{aligned} T_{2p}(W, f) &= (-1)^{p-1} \frac{B_p}{(2p)!} \int_{e_1}^* \mathrm{D}^{2p-1} f \cdot (w_2(v), \dots, w_2(v)) \\ &\quad + (-1)^{p-1} \frac{B_p}{(2p)!} \int_{e_2}^* \mathrm{D}^{2p-1} f \cdot (w_1(v), \dots, w_1(v)) \\ &\quad + (-1)^{p-2} \sum_{\substack{m+\ell=p, \\ m, \ell \geq 1}} \frac{B_m B_\ell}{(2m)!(2\ell)!} \mathrm{D}^{2p-2} f(v) \cdot \underbrace{(w_1(v), \dots, w_1(v))}_{2m-1 \text{ times}} \underbrace{(w_2(v), \dots, w_2(v))}_{2\ell-1 \text{ times}}. \end{aligned}$$

We write

$$\begin{aligned} \int_{e_j}^* \mathrm{D}^{2p-1} f \cdot (w_i(v), \dots, w_i(v)) &= \eta_j(v) \int_{e_j}^* \mathrm{D}^{2p-1} f \cdot (w_j(v), w_i(v), \dots, w_i(v)) \\ &\quad + \zeta(e_j) \int_{e_j}^* \mathrm{D}^{2p-1} f \cdot (n_j, w_i(v), \dots, w_i(v)). \end{aligned}$$

By Lemma 5.1, we have

$$\int_{e_j}^* \mathrm{D}^{2p-1} f \cdot (w_j(v), w_i(v), \dots, w_i(v)) = -\mathrm{D}^{2p-2} f \cdot (w_i(v), \dots, w_i(v)),$$

hence we obtain

$$\begin{aligned} \int_{e_j}^{\star} D^{2p-1} f \cdot (w_i(v), \dots, w_i(v)) &= -\eta_j(v) D^{2p-2} f \cdot (w_i(v), \dots, w_i(v)) \\ &\quad + \zeta(e_j) \int_{e_j}^{\star} D^{2p-1} f \cdot (n_j, w_i(v), \dots, w_i(v)). \end{aligned}$$

By induction, this yields

$$\begin{aligned} &\int_{e_j}^{\star} D^{2p-1} f \cdot (w_i(v), \dots, w_i(v)) \\ &= -\eta_j(v) \sum_{k=0}^{2p-2} \zeta(e_j)^k D^{2p-2} f \cdot \underbrace{(n_j, \dots, n_j)}_{k \text{ times}}, \underbrace{(w_i(v), \dots, w_i(v))}_{2p-2-k \text{ times}} \\ &\quad + \zeta(e_j)^{2p-1} \int_{e_j}^{\star} D^{2p-1} f \cdot (n_j, \dots, n_j). \end{aligned}$$

The case $q = 2p + 1$ works in a similar way. \square

8. EXAMPLES

Let us describe two examples in the two-dimensional case. The first one is explicit, in the sense that we choose a function for which the asymptotic expansion given in Theorem 6.1 is finite, and we provide every coefficient of the latter. For the second one, we compute the first three terms of the asymptotic expansion and give numerical computations of the remainder.

8.1. An explicit example. Let Δ be the triangle with vertices $(0, 0)$, $(0, 1)$ and $(1, 0)$ and let

$$f : \mathbb{R}^2 \rightarrow \mathbb{R}$$

be the function defined by

$$f(x_1, x_2) = x_1$$

(multiplied by a cutoff function so that it is compactly supported). Then

$$\mathbb{Z}^2 \cap N\Delta = \{(k_1, k_2) \in \mathbb{Z}^2, \quad 0 \leq k_1 \leq N, \quad 0 \leq k_2 \leq N - k_1\}.$$

Therefore, we have that

$$\frac{1}{N^2} \sum_{k \in N\Delta \cap \mathbb{Z}^2} f\left(\frac{k}{N}\right) = \frac{1}{N^2} \sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} \frac{k_1}{N} = \frac{1}{N^3} \left((N+1) \sum_{k_1=1}^N k_1 - \sum_{k_1=1}^N k_1^2 \right).$$

Using standard formulas for sums of integers and squares of integers, one can check that

$$\frac{1}{N^2} \sum_{k \in N\Delta \cap \mathbb{Z}^2} f\left(\frac{k}{N}\right) = \frac{1}{6} + \frac{1}{2N} + \frac{1}{3N^2}.$$

Let us compare this with Theorem 7.2. With the notation of this theorem, we have

$$T_0(\Delta, f) = \int_{\Delta} f = \int_0^1 \left(\int_0^{1-x_1} dx_2 \right) x_1 dx_1 = \frac{1}{6}$$

so the zeroth order terms agree. Let us give names to the vertices and edges of Δ as follows: we put $v_{13} = (0, 0)$, $v_{12} = (0, 1)$ and $v_{23} = (1, 0)$, and we let e_i denote the edge joining the vertices v_{ij} (or v_{ji}) and v_{ik} (or v_{ki}). Then we have

$$\int_{e_1}^* f = 0, \quad \int_{e_2}^* f = \frac{1}{2}, \quad \int_{e_3}^* f = \frac{1}{2}.$$

and hence

$$T_1(\Delta, f) = 1/2.$$

Furthermore, we have

$$T_2(\Delta, f) = S - T$$

with

$$S = \sum_{v \in V} \left(\frac{1}{4} + \frac{\mu(v)}{12} \right) f(v), \quad T = \frac{1}{12} \sum_{e \in E} \zeta(e) \int_e^* Df \cdot n_e.$$

We have $f(v_{13}) = 0$, $f(v_{12}) = 0$, $f(v_{23}) = 1$. Moreover

$$w_1(v_{23}) = \begin{pmatrix} -1 \\ 0 \end{pmatrix}, \quad w_2(v_{23}) = \begin{pmatrix} -1 \\ 1 \end{pmatrix}$$

and thus $\mu(v_{23}) = 3/2$. This yields $S = 3/8$. Now, one can check that

$$\int_{e_1}^* Df \cdot n_{e_1} = -1, \quad \int_{e_2}^* Df \cdot n_{e_2} = 1, \quad \int_{e_3}^* Df \cdot n_{e_3} = 0$$

and $\zeta(e_1) = -1$, $\zeta(e_2) = -\frac{1}{2}$. We obtain $T = 1/24$ and therefore

$$T_2(\Delta, f) = 1/3.$$

Finally, we have

$$T_q(\Delta, f) = 0, \quad q \geq 2$$

because the derivatives of f of order greater than two vanish.

8.2. Numerical computations. Let Δ be as in the previous paragraph, and consider the function

$$f : \mathbb{R}^2 \setminus \{(x_1, x_2) \in \mathbb{R}^2; x_1 + x_2 = -1\} \rightarrow \mathbb{R}, \quad (x_1, x_2) \mapsto \frac{1}{1 + x_1 + x_2}.$$

We want to evaluate the sum

$$S_N := \frac{1}{N^2} \sum_{k \in N\Delta \cap \mathbb{Z}^2} f\left(\frac{k}{N}\right) = \frac{1}{N^2} \sum_{k_1=0}^N \sum_{k_2=0}^{N-k_1} \frac{1}{1 + \frac{k_1+k_2}{N}}.$$

Let us compute the coefficients $T_i(\Delta, f)$, $i = 0, 1, 2$, of the asymptotic expansion given in Theorem 6.1. Firstly, we have

$$T_0(\Delta, f) = \int_0^1 \left(\int_0^{1-x_1} \frac{dx_2}{1+x_1+x_2} \right) dx_1 = \log 2 - \int_0^1 \log(1+x_1) dx_1 = 1 - \log 2.$$

Secondly, notice that

$$\int_{e_1}^* f = \int_0^1 \frac{dx_2}{1+x_2} = \log 2, \quad \int_{e_2}^* f = \int_0^1 \frac{dx_1}{1+x_1} = \log 2, \quad \int_{e_1}^* f = \frac{1}{2},$$

and hence

$$T_1(\Delta, f) = \frac{1}{4} + \log 2.$$

Finally, since

$$f(v_{13}) = 1, \quad f(v_{23}) = \frac{1}{2}, \quad f(v_{12}) = \frac{1}{2}$$

and

$$\mu(v_{13}) = 0, \quad \mu(v_{23}) = \frac{3}{2}, \quad \mu(v_{12}) = \frac{3}{2}$$

we obtain

$$\sum_{v \in V} \left(\frac{1}{4} + \frac{\mu(v)}{12} \right) f(v) = \frac{30}{48}$$

(we deliberately keep this fraction as it is, which will make sense in view of the next result). Moreover, we have

$$\int_{e_1}^* Df \cdot n_{e_1} = \int_0^1 \frac{dx_2}{(1+x_2)^2} = \frac{1}{2}, \quad \int_{e_2}^* Df \cdot n_{e_2} = -\frac{1}{2}, \quad \int_{e_3}^* Df \cdot n_{e_3} = \frac{1}{2}$$

and

$$\zeta(e_1) = -1, \quad \zeta(e_2) = -\frac{1}{2}, \quad \zeta(e_3) = -1;$$

thus

$$\frac{1}{12} \sum_{e \in E} \zeta(e) \int_e^* Df \cdot n_e = \frac{3}{48}.$$

We deduce from the previous results that

$$T_2(\Delta, f) = \frac{33}{48}.$$

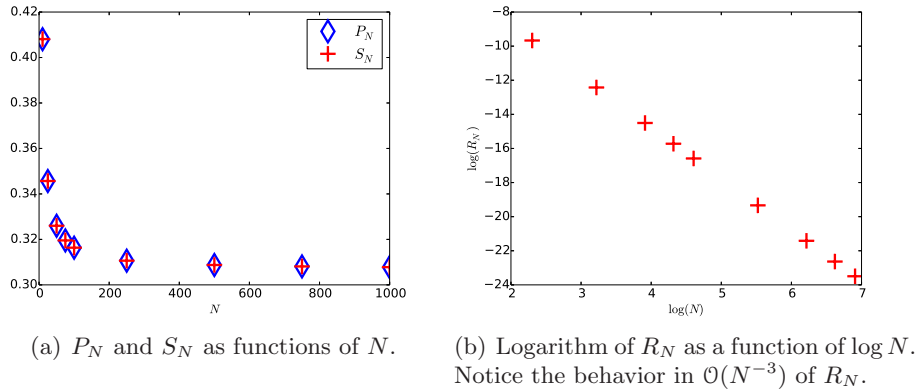
We can now compute

$$P_N := T_0(\Delta, f) + T_2(\Delta, f)N^{-1} + T_2(\Delta, f)N^{-2};$$

in Figure 3, we compare the value of P_N to the numerical value of S_N , for $N = 10, 25, 50, 75, 100, 250, 500, 750, 1000$, and we numerically evaluate the quantity

$$R_N = |S_N - P_N|;$$

more precisely, we plot the value of $\log R_N$ as a function of $\log N$. The remainder R_N displays a behavior in $\mathcal{O}(N^{-3})$, as expected.

FIGURE 3. Comparison between P_N and R_N .

9. FINAL REMARKS

We believe that one should be able to prove item (ii) in Theorem 2.1 in dimensions $n \geq 4$ with the same elementary method that we use in this paper (since a similar result was already stated in Tate’s article in any dimension). However, in dimensions $n \geq 4$ the computations appear to be more complicated and will be the object of future work (see also Remark 5.5).

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