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To cite this version:
Velleda Baldoni, Arzu Boysal, Michele Vergne. Multiple Bernoulli series and volumes of moduli spaces of flat bundles over surfaces. MEGA’2013 (Special Issue), Jun 2013, Frankfurt am Main, Allemagne.
hal-01022885

HAL Id: hal-01022885
https://hal.science/hal-01022885
Submitted on 11 Jul 2014

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Multiple Bernoulli series and volumes of moduli spaces of flat bundles over surfaces

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Abstract

Using Szenes formula for multiple Bernoulli series, we explain how to compute Witten series associated to classical Lie algebras. Particular instances of these series compute volumes of moduli spaces of flat bundles over surfaces, and also certain multiple zeta values.

Keywords: multiple Bernoulli series, moduli spaces of flat connections, multiple zeta values

Introduction

Let $V$ be a finite dimensional real vector space, and $\Lambda$ a lattice in $V$. We denote the dual of $\Lambda$ by $\Gamma$.

We consider a finite sequence of vectors $\Phi$ lying in $\Lambda$, and let $\Gamma_{\text{reg}}(\Phi) = \{ \gamma \in \Gamma | \langle \phi, \gamma \rangle \neq 0, \text{ for all } \phi \in \Phi \}$ be the set of regular elements in $\Gamma$ relative to $\Phi$.

In this paper we compute

$$B(\Phi, \Lambda)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}(\Phi)} \prod_{\phi \in \Phi} e^{(2i\pi \phi, \gamma)}$$

a function on the torus $V/\Lambda$. This sum, if not absolutely convergent, has a meaning as a generalized function. If $\Phi$ generates $V$, then $B(\Phi, \Lambda)$ is piecewise polynomial (see [12]).

For example, for $V = \mathbb{R}e_1 \oplus \mathbb{R}e_2$ with standard lattice $\Lambda = \mathbb{Z}e_1 \oplus \mathbb{Z}e_2$, if we choose $\Phi = [e_1, e_1, e_2, e_1 + e_2, e_1 - e_2]$, then

$$B(\Phi, \Lambda)(v_1e_1 + v_2e_2) = \sum_{n_1, n_2} e^{2i\pi(n_1 + n_2)}$$

$$\frac{(2i\pi n_1) (2i\pi n_2)}{(2i\pi(n_1 + n_2))(2i\pi(n_1 + n_2))},$$

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where the summation $\sum'$ means that we sum only over the integers $n_1$ and $n_2$ such that $n_1, n_2(n_1 + n_2)(n_1 - n_2) \neq 0$. The expression for $\mathcal{B}(\Phi, \Lambda)(v_1 e_1 + v_2 e_2)$ as a piecewise polynomial function of $v_1$ and $v_2$ (of degree 5) is given in Section 2, Equation (2.6.2).

We call $\mathcal{B}(\Phi, \Lambda)$ the \textit{multiple Bernoulli series} associated to $\Phi$ and $\Lambda$. Multiple Bernoulli series have been extensively studied by A. Szenes ([12],[13]). They are natural generalizations of Bernoulli series: for $\nu = \mathbb{R}_+, \Lambda = \mathbb{Z}_\nu$ and $\Phi_k = [\omega; \omega; \ldots; \omega]$, where $\omega$ is repeated $k$ times with $k > 0$, the function

$$\mathcal{B}(\Phi_k, \Lambda)(t \omega) = \sum_{n \in \mathbb{Z}, n \neq 0} \frac{e^{2i\pi n t}}{(2i\pi n)^k}$$

is equal to $-\frac{1}{k} B(k, \{t\})$ where $B(k, t)$ denotes the $k^{th}$ Bernoulli polynomial in variable $t$, and $\{t\} = t - \lfloor t \rfloor$ is the fractional part of $t$. If $k = 2g$ and $t = 0$, due to the symmetry $n \to -n$,

$$\mathcal{B}(\Phi_{2g}, \Lambda)(0) = 2 \frac{1}{(2i\pi)^{2g}} \zeta(2g).$$

From the residue theorem in one variable, for $k > 0$,

$$\sum_{n \in \mathbb{Z}, n \neq 0} \frac{e^{2i\pi n t}}{(2i\pi n)^k} = \text{Res}_{z=0} \left( \frac{1}{z^k} e^{zt} \frac{1}{1 - e^z} \right).$$

Szenes multidimensional residue formula (cf. Theorem 1.27) is the generalization of this formula to higher dimensions, and it is the tool that we use for computing $\mathcal{B}(\Phi, \Lambda)(v)$ as a piecewise polynomial function.

A particular but crucial instance of multiple Bernoulli series is when $\Lambda$ is the coroot lattice of a compact connected simple Lie group $G$, and $\Phi$ is comprised of positive coroots of $G$. The series $\mathcal{B}(\Phi_{2g-2}, \Lambda)$, where the argument $\Phi_{2g-2}$ refers to taking elements of $\Phi$ with multiplicity $2g - 2$, appeared in the work of E. Witten ([16], §3), where Witten shows that its value at $v = 0$ (up to a scalar depending on $G$ and $g$) is the symplectic volume of the moduli space of flat $G$-connections on a Riemann surface of genus $g$. Similarly, for a collection of \textit{regular} elements $v = \{v_1, \ldots, v_s\}$ of the Cartan Lie algebra of $G$, certain linear combinations of $\mathcal{B}(\Phi_{2g-2+s}, \Lambda)$ at some particular values (depending on $v$) is the symplectic volume of the moduli space of flat $G$-connections on a Riemann surface of genus $g$ with $s$ boundary components, around which the holonomy is determined by $v$. Then, its dependence on $v$ is piecewise polynomial.

Multiple Bernoulli series have also been studied by P.E. Gunnells and R. Sczech ([5]) in view of applications to zeta functions of real number fields. Explicit computations of volumes of moduli spaces of flat bundles on Riemann surfaces are also obtained in [5]. Yet, the techniques they use is a generalization of the continued fraction algorithm and it is different from ours.

Y. Komori, K. Matsumoto and H. Tsumura ([6],[7],[8],[9]) studied the restriction of the series (0.0.1), by summing it over the cone of dominant regular
weights of a semi-simple Lie group $G$, and defined a function $\zeta(s, v, G)$ (cf. Section 5.2). They also obtained relations between these functions over $\mathbb{Q}$. When $\Lambda$ is the coroot lattice of a compact connected simple Lie group $G$ and the sequence $\Phi$ is the set of its positive coroots with equal even multiplicity for long roots and (possibly different) equal even multiplicity for short roots, due to the Weyl group symmetry, the summation $\mathcal{B}(\Phi, \Lambda)(0)$ over the full (regular) weight lattice is just (up to multiplication by an appropriate power of $(2\pi)$) Komori-Matsumoto-Tsumura zeta function $\zeta(s, 0, G)$. Thus, the value of $\zeta(s, 0, G)$ (up to a certain power of $(2\pi)$) is a rational number which can be computed explicitly; we give examples of such computations. As it is observed in [6], some instances of $\zeta(s, v, G)$ also compute certain multiple zeta values. In the last part of the article we give various such computations of multiple zeta values using $\mathcal{B}(\Phi, \Lambda)$.

Here is the outline of individual sections.

In Section 1, we recall a formula due to A. Szenes, which allows an efficient computation of $\mathcal{B}(\Phi, \Lambda)$.

In Section 2, we give an outline of an algorithm that efficiently computes the needed ingredients of this formula for classical root systems. We also give several simple examples.

In Section 3, we show how this applies to the symplectic volume of the moduli space of flat $G$-connections on a Riemann surface of genus $g$ with $s$ boundary components. We obtain an expression for the symplectic volume by taking the limit of the Verlinde formula. We then show that our formula thus obtained coincides with that of Witten (including the constants) given in terms of the Riemannian volumes of $G$ and $T$. We also give examples of these functions.

In Sections 4 and 5, we give several examples and tables of Witten volumes, which include some examples from [6], [7], [8] and [9]. We give an idea of computational limitation of our algorithm (written as a simple Maple program) in terms of the rank of the group $G$ and the number of elements in $\Phi$. Following Komori-Matsumoto-Tsumura, we also give some examples of rational multiple zeta values. To compute more examples, our Maple program is available on the webpage of the last author.

Finally, in the appendix, for completeness, we include a slightly modified proof of Szenes formula.

Acknowledgements

Part of this work was completed when all three authors were at Mathematisches Forschungsinstitut Oberwolfach as a part of Research in Pairs programme in February 2012. We would like to express our gratitude to the institute for their hospitality.

The first author was partially supported by a PRIN2009 grant, the second author was partially supported by Boğaziçi University (B.U.) Research Fund 5076. The third author wishes to thank Boğaziçi University for support of research visits.

We also thank Shrawan Kumar, and the referees for their suggestions.
1. Szenes formula for multiple Bernoulli series

1.1. Functions on the complement of hyperplanes

In this subsection $U$ is an $r$-dimensional complex vector space. We denote its dual by $V$. If $\phi \in V$, we denote by $H_{\phi} = \{ u \in U; \langle \phi, u \rangle = 0 \}$ the hyperplane in $U$ determined by $\phi$.

We recall briefly some structure theorems for the ring of rational functions that are regular on the complement of a union of hyperplanes [4].

Let $\mathcal{H} = \{ H_1, \ldots, H_N \}$ be a set of hyperplanes in $U$. Then, we may choose $\phi_k \in V$ such that $H_k = H_{\phi_k}$; the element $\phi_k$ is called an equation of $H_k$. Clearly, an equation $\phi_k$ is not unique, it is determined up to a non-zero scalar multiple. Consider $U_H := \{ u \in U; \langle \phi_k, u \rangle \neq 0 \text{ for all } k \}$, an open subset of $U$; an element of $U_H$ is called regular.

We denote by $S(V)$ the symmetric algebra of $V$ and identify it with the ring of polynomial functions on $U$. Let $\mathcal{R}_{\mathcal{H}}$ denote the ring of rational functions on $U$ that are regular on $U_{\mathcal{H}}$, that is, the ring generated by $S(V)$ together with inverses of the linear forms $\phi_k$ defining $\mathcal{H}$.

The ring $D(U)$ of differential operators on $U$ with polynomial coefficients acts on $\mathcal{R}_{\mathcal{H}}$. In particular, $U$ operates on $\mathcal{R}_{\mathcal{H}}$ by differentiation. We denote by $\partial(U)\mathcal{R}_{\mathcal{H}}$ the subspace of $\mathcal{R}_{\mathcal{H}}$ obtained by differentiation.

In the particular case that $V$ is one dimensional and $\mathcal{H} = \{0\}$, the ring $\mathcal{R}_{\mathcal{H}}$ is the ring of Laurent polynomials $\mathbb{C}[z, z^{-1}]$, and the function $z^i$, for $i \neq -1$, is obtained as a derivative $\frac{d}{dz} \frac{1}{z+i+1} z^{i+1}$. Thus $\mathcal{R}_{\mathcal{H}} = \frac{d}{dz} \mathcal{R}_{\mathcal{H}} \oplus \mathbb{C} z^{-1}$.

If $f = \sum_n a_n z^n$ is an element of $\mathbb{C}[z, z^{-1}]$, we denote by $\text{Res}_{z=0} f$ the coefficient $a_{-1}$ of $z^{-1}$ in the expression of $f$. The linear form $\text{Res}_{z=0}$ is characterized by the fact that it vanishes on $\frac{d}{dz} \mathcal{R}_{\mathcal{H}}$ and takes the value $a_{-1}$ on $\mathbb{C} z^{-1}$.

By analogy to the one dimensional case demonstrated above, a linear functional on $\mathcal{R}_{\mathcal{H}}$ vanishing on $\partial(U)\mathcal{R}_{\mathcal{H}}$ will be called a ‘residue’.

Let us thus analyze the space $\mathcal{R}_{\mathcal{H}}$ modulo $\partial(U)\mathcal{R}_{\mathcal{H}}$.

Consider a set $\Phi^q := \{ \phi_1, \phi_2, \ldots, \phi_N \}$ of equations for $\mathcal{H}$. A subset $\sigma$ of $\Phi^q$ will be called a basis if the elements $\phi_k$ in $\sigma$ form a basis of $V$. We denote by $\mathcal{B}(\Phi^q)$ the set of such subsets $\sigma$. A subset $\nu$ of $\Phi^q$ will be called generating if the elements $\phi_k$ in $\nu$ generate the vector space $V$.

**Definition 1.1.** Let $\sigma := \{ \alpha_1, \alpha_2, \ldots, \alpha_r \} \in \mathcal{B}(\Phi^q)$. The element

$$f_\sigma(z) := \frac{1}{\prod_{k=1}^r \alpha_k(z)}$$

of $\mathcal{R}_{\mathcal{H}}$ is called a ‘simple fraction’. We denote by $S_\mathcal{H}$ the subspace of $\mathcal{R}_{\mathcal{H}}$ generated by the elements $f_\sigma$, $\sigma \in \mathcal{B}(\Phi^q)$.

Let $\nu = [\alpha_1, \ldots, \alpha_k]$ be a sequence of $k$ elements of $\Phi^q$ and $n = [n_1, n_2, \ldots, n_k]$ be a sequence of positive integers. We define

$$\theta(\nu, n) = \frac{1}{\alpha_1^{n_1} \cdots \alpha_k^{n_k}}.$$
We denote by $G_{\mathcal{H}}$ the subspace of $\mathcal{R}_\mathcal{H}$ generated by the elements $\theta(\nu, n)$ where $\nu$ is generating.

As the notation suggests, the spaces $\mathcal{R}_\mathcal{H}$, $\mathcal{S}_\mathcal{H}$ and $G_{\mathcal{H}}$ depend only on $\mathcal{H}$. The term simple fraction comes from the fact that if $\sigma = \{\phi_1, \phi_2, \ldots, \phi_r\}$ is a basis, then we can choose coordinates $z_i$ on $U$ so that $\phi_i(z) = z_i$, so that for this system of coordinates $f_\sigma(z) = \prod_{i=1}^r z_i$.

We recall the following 'partial fraction' decomposition result from [4].

Lemma 1.2. Let $\nu$ be a subset of $\Phi^{eq}$ generating a $t$ dimensional subspace of $V$. Then $\theta(\nu, n)$ may be written as a linear combination of elements $\theta(\sigma, m) = \frac{1}{\alpha_1 \cdots \alpha_t}$ where $\sigma := \{\alpha_1, \ldots, \alpha_t\}$ is a subset of $\nu$ consisting of $t$ independent elements and $m = \{m_1, \ldots, m_r\}$ a sequence of positive integers.

Example 1.3. $\frac{1}{z_1 z_2 (z_1 + z_2)} = \frac{1}{z_1 (z_1 + z_2)^2} + \frac{1}{z_2 (z_1 + z_2)^2}$.

Theorem 1.4. (Brion-Vergne [4]) $\mathcal{R}_\mathcal{H} = \partial(U) \mathcal{R}_\mathcal{H} \oplus \mathcal{S}_\mathcal{H}$.

The projector $R : \mathcal{R}_\mathcal{H} \rightarrow \mathcal{S}_\mathcal{H}$ will be called the total residue. In view of this theorem, a residue is just a linear form on $\mathcal{S}_\mathcal{H}$.

In the case that $\mathcal{H}$ is the set of hyperplanes with equations the positive coroots of a simple compact Lie group $G$, the dimension of $\mathcal{S}_\mathcal{H}$ is given by the product of exponents of $G$ [11]. In Section 2, we will give an explicit basis for $\mathcal{S}_\mathcal{H}$ for simple Lie algebras of type $A$, $B$ and $C$ (which defines the same set of hyperplanes as $B$) with dual basis consisting of iterated residues.

1.2. Szemes polynomial

In this section and for the rest of the article, $V$ will denote a real vector space of dimension $r$.

Let $U$ be the dual vector space of $V$. Let $\Lambda$ be a lattice in $V$ with dual lattice $\Gamma$ in $U$.

Let $\mathcal{H} := \{H_1, H_2, \ldots, H_N\}$ be a real arrangement of hyperplanes in $U$. We say that $\Lambda$ and $\mathcal{H}$ are compatible if the hyperplanes in $\mathcal{H}$ are rational with respect to $\Lambda$, that is, they can be defined by equations $\phi_k \in \Lambda$. If $\Lambda'$ is another lattice commensurable with $\Lambda$, then $\Lambda'$ and $\mathcal{H}$ are also compatible.

Thus we now consider a lattice $\Lambda$ and a real arrangement of hyperplanes $\mathcal{H} = \{H_1, H_2, \ldots, H_N\}$ in $U$ rational with respect to $\Lambda$.

We choose $\Phi^{eq} = \{\phi_1, \phi_2, \ldots, \phi_N\}$, a set of defining equations for $\mathcal{H}$, with each $\phi_i$ in $\Lambda$. We sometimes refer to $\mathcal{H}$ only via its set of equations $\Phi^{eq}$ and write $\mathcal{H} = \cup \{\phi_k = 0\}$.

We denote the complex arrangement defined by $\cup \{\phi_k = 0\}$ in $U_C$ with the same letter $\mathcal{H}$, and denote by $U_{\mathcal{H}} = \{\prod_k \phi_k \neq 0\}$ the corresponding open subset of $U_C$.
An admissible hyperplane $W$ in $V$ (for the system $\mathcal{H}$) is a hyperplane generated by $(r-1)$ linearly independent elements $\phi_k$ of $\Phi^{eq}$. Such an hyperplane will also be called an (admissible) wall. An admissible affine wall is a translate of a wall by an element of $\Lambda$.

An element $v \in V$ is called regular for $(\mathcal{H}, \Lambda)$ if $v$ is not on any affine wall (we will simply say that $v$ is regular). The meaning of the word regular is thus different for elements $v \in V$ (v is not on any affine wall) and $u \in U_C$ ($u$ is such that $\prod_k \langle \phi_k, u \rangle \neq 0$). However, it will be clear what regular means in the context.

A tope $\tau$ is a connected component of the complement of all affine hyperplanes. Thus a tope $\tau$ is a connected open subset of $V$ consisting of regular elements. We denote the set of toposes by $T(\mathcal{H}, \Lambda)$. As the notation indicates, $T(\mathcal{H}, \Lambda)$ does not depend on the choice of equations for $\mathcal{H}$.

Example 1.5. Let $V = \mathbb{R}e_1 \oplus \mathbb{R}e_2$ and $\Lambda = \mathbb{Z}e_1 \oplus \mathbb{Z} e_2$. Let $U$ be its dual with basis $\{e_1, e_2\}$. We express $z \in U_C$ as $z = z_1e_1 + z_2 e_2$, and consider the set of hyperplanes $\mathcal{H} = \{\{z_1 = 0\}, \{z_2 = 0\}, \{z_1 + z_2 = 0\}\}$ with the set of equations $\Phi^{eq} = \{e_1, e_2, e_1 + e_2\}$. Figure 1 depicts topes associated to this pair.

Example 1.6. With $V$ and $\Lambda$ as above, we now consider the set of hyperplanes $\mathcal{H} = \{\{z_1 = 0\}, \{z_2 = 0\}, \{z_1 + z_2 = 0\}, \{z_1 - z_2 = 0\}\}$ with the set of equations $\Phi^{eq} = \{e_1, e_2, e_1 + e_2, e_1 - e_2\}$. Figure 2 depicts topes associated to this pair.

We denote by $V_{reg}(\mathcal{H}, \Lambda)$ (or simply $V_{reg}$) the set of $(\mathcal{H}, \Lambda)$ regular elements of $V$. It is an open subset of $V$ which is the disjoint union of all toposes.

A locally constant function on $V_{reg}$ is a function on $V_{reg}$ which is constant on each tope. A piecewise polynomial function on $V_{reg}$ is a function on $V_{reg}$ which is given by a polynomial expression on each tope.

If $t \in \mathbb{R}$, we denote by $\lfloor t \rfloor$ the integral part of $t$, and by $\{t\} = t - \lfloor t \rfloor$ the fractional part of $t$. If $\gamma \in \Gamma$ vanishes on an admissible hyperplane $W$, and $c$ is a constant, then the function $v \mapsto \{\langle \gamma, v \rangle + c\}$ is piecewise polynomial (piecewise linear) and is periodic with respect to $\Lambda$. Szenes residue formula provides an algorithm to describe Bernoulli series in terms of these basic functions.

Figure 1: Topes for Example 1.5  
Figure 2: Topes for Example 1.6

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**Definition 1.7.** Let $\mathcal{M}_H$ be the space of functions $h/Q$ where $Q$ is a product of linear forms belonging to $\Phi^{eq}$, and $h$ a holomorphic function defined in a neighborhood of $0$ in $U_C$.

We define the space $\mathcal{R}_H$ as the space of functions $\hat{h}/Q$ where $\hat{h} = \sum_{k=0}^{\infty} P_k$ is a formal power series and $Q$ is a product of linear forms belonging to $\Phi^{eq}$.

Taking the Taylor series $\hat{h}$ of $h$ at $0$ defines an injective map from $\mathcal{M}_H$ to $\mathcal{R}_H$. The projector $R$ from $\mathcal{R}_H$ to $\mathcal{S}_H$ extends to $\mathcal{R}_H$. Indeed $R$ vanishes outside the homogeneous components of degree $-r$ of the graded space $\mathcal{R}_H$. Thus if $h = P_k$ is an element in $\mathcal{M}_H$, with $Q$ a product of $N$ elements of $\Phi^{eq}$, we take the Taylor series $\hat{h}$ of $h$ at $0$.

Let $f \in \mathcal{R}_H$, $z \in U_H$ and $v \in \mathcal{S}_H$. Then if $z$ is small, $2i\pi \gamma - z$ is still a regular element of $U_C$. Now consider the series

$$S(f, z, v) = \sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{(v, 2i\pi \gamma)}.$$

In the case that $f$ above decreases sufficiently quickly at infinity, the series $S(f, z, v)$ is absolutely convergent and defines a continuous function of $v$. In general, as $f \in \mathcal{R}_H$ is of at most polynomial growth, $\sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{(v, 2i\pi \gamma)}$ is the Fourier series of a generalized function on $V/\Lambda$.

Multiplying $S(f, z, v)$ by the exponential $e^{-z, v)}$ we introduce the following generalized function.

**Definition 1.8.** Let $f \in \mathcal{R}_H$, $z \in U_H$ and small. We define the generalized function $A^\Lambda(f)(z, v)$ of $v$ by

$$A^\Lambda(f)(z, v) = \sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{(v, 2i\pi \gamma - z)}.$$

The meaning of $A^\Lambda(f)$ is clear: average the function $z \mapsto f(-z)e^{-(v, z)}$ over $2i\pi \Gamma$ in order to obtain a function on the complex torus $U_C/2i\pi \Gamma$. We consider $A^\Lambda(f)(z, v)$ as a generalized function of $v \in V$ with coefficients meromorphic functions of $z$ on $U_C/2i\pi \Gamma$. In fact, as we shall see in Proposition 1.11, when $f$ is in $\mathcal{S}_H$, the convergence of the series $\sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{(v, 2i\pi \gamma)}$ holds in the
sense of the Fourier series of an $L^2$-periodic function of $v \in V/\Lambda$, and

$$v \mapsto e^{-\langle v, z \rangle} \left( \sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{\langle v, 2i\pi \gamma \rangle} \right) = A^\Lambda(f)(z, v)$$

is a locally constant function of $v \in V_{reg}$ with values in $\mathcal{M}_H$.

Note the covariance relation. For $\lambda \in \Lambda$,

$$A^\Lambda(f)(z, v + \lambda) = e^{-\langle \lambda, z \rangle} A^\Lambda(f)(z, v). \quad (1.8.1)$$

It is easy to compare $A^\Lambda(f)(z, v)$ when we change the lattice $\Lambda$.

**Lemma 1.9.** Let $f \in \mathcal{R}_H$. If $\Lambda^1 \subset \Lambda^2$, then

$$A^{\Lambda^2}(f)(z, v) = |\Lambda^2/\Lambda^1|^{-1} \sum_{\lambda \in \Lambda^2/\Lambda^1} A^{\Lambda^1}(f)(z, v + \lambda). \quad (1.9.1)$$

**Proof.** Denote the dual of $\Lambda^i$ by $\Gamma^i$. Then,

$$A^{\Lambda^i}(f)(z, v + \lambda) = \sum_{\gamma \in \Gamma^i} f(2i\pi \gamma - z)e^{\langle v + \lambda, 2i\pi \gamma - z \rangle},$$

and the sum over $\lambda \in \Lambda^2/\Lambda^1$ of $e^{\langle \lambda, 2i\pi \gamma \rangle}$ is zero except when $\gamma \in \Gamma^2$. $\square$

**Example 1.10.** Let $V = \mathbb{R}$, $\Lambda = \mathbb{Z}$, $z \in \mathbb{C} \setminus \{0\}$ and small, and $f(z) = \frac{1}{z}$. Then,

$$A^\Lambda(f)(z, v) = \sum_{n \in \mathbb{Z}} \left( \frac{e^{(2i\pi n - z)}}{2i\pi n - z} \right) = e^{-z} \sum_{n \in \mathbb{Z}} \frac{e^{2i\pi n v}}{2i\pi n - z}.$$

This series is not absolutely convergent, but the oscillatory factor $e^{2i\pi n v}$ assures the convergence in the distributional sense as a function of $v$. The $L^2$-expansion of the periodic function $v \mapsto \frac{e^{-\langle v, z \rangle}}{1 - e^z}$ is

$$\sum_{n \in \mathbb{Z}} \left( \int_0^1 \frac{e^{(v-|v|)u}}{1 - e^u} e^{-2i\pi n v} du \right) e^{2i\pi n v} = \sum_{n \in \mathbb{Z}} \left( \int_0^1 \frac{e^{v(z-2i\pi n)}}{1 - e^u} du \right) e^{2i\pi n v}$$

$$= \sum_{n \in \mathbb{Z}} \frac{e^{(z-2i\pi n)} - 1}{(1 - e^z)(z - 2i\pi n)} e^{2i\pi n v} = \sum_{n \in \mathbb{Z}} \frac{1}{(2i\pi n - z)} e^{2i\pi n v}.$$

Thus

$$A^\Lambda(f)(z, v) = \frac{e^{-|v| z}}{1 - e^z}. \quad (1.10.1)$$

We see in this one dimensional example that $A^\Lambda(f)(z, v)$ is a locally constant function of $v$. In general, we have the following proposition.

**Proposition 1.11.** If $f \in \mathcal{S}_H$, the function $v \mapsto A^\Lambda(f)(z, v)$ is a locally constant function on $V_{reg}$, with values in $\mathcal{M}_H$. 

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We prove the above proposition by computing \( A^\Lambda(f)(z, v) \) explicitly for a simple fraction \( f = f_\sigma \). Then the result will follow for any \( f \in \mathcal{S}_H \).

Recall that the set of equations \( \Phi^{eq} \) is a subset of \( \Lambda \). Let \( \sigma = \{ \alpha_1, \alpha_2, \ldots, \alpha_r \} \) be an element of \( \mathfrak{B}(\Phi^{eq}) \), with \( \alpha_k \) belonging to \( \Lambda \). Let \( Q_\sigma := \oplus_{k=1}^r [0,1) \alpha_k \) be the semi-open parallelepiped spanned by \( \sigma \). For a regular element \( v \) in \( V \), we define \( T(v, \sigma) \) to be the set of elements \( \lambda \in \Lambda \) such that \( v + \lambda \in Q_\sigma \). This set depends only on the tope \( \tau \) where \( v \) belongs, hence we denote it by \( T(\tau, \sigma) \).

Let \( \Lambda_\sigma \) be the sublattice of \( \Lambda \) generated by the elements in the basis \( \sigma \). Then the set \( T(\tau, \sigma) \) contains exactly \( \Lambda/\Lambda_\sigma \) elements.

**Proposition 1.12.** If \( v \in \tau \) and \( \sigma = \{ \alpha_1, \alpha_2, \ldots, \alpha_r \} \in \mathfrak{B}(\Phi^{eq}) \),

\[
A^\Lambda(f_\sigma)(z, v) = \frac{1}{|\Lambda/\Lambda_\sigma|} \sum_{\lambda \in T(\tau, \sigma)} e^{(\lambda, z)} \prod_{i=1}^{r} (1 - e^{(\alpha_i, z)})^{-1}.
\]

**Proof.** If \( \Lambda = \Lambda_\sigma \), the formula reduces to the one dimensional case. Otherwise, we use Lemma 1.9 and the covariance relation (1.8.1). \qed

Thus the dependence of \( A^\Lambda(f_\sigma)(z, v) \) on \( v \) is only via the tope \( \tau \) where it belongs. Therefore, for any \( f \in \mathcal{S}_H \), the function \( A^\Lambda(f)(z, v) \) is locally constant on \( V_{reg} \). Hence the claim in Proposition 1.11.

**Example 1.13.** We return to Example 1.5. To describe \( A^\Lambda(f)(z, v) \) on \( V_{reg} \), it suffices to give its expression on topes \( \tau_1 \) and \( \tau_2 \) (see Figure 1). This is true since any element of \( V_{reg} \) can be translated to \( \tau_1 \) or \( \tau_2 \) by an element of \( \Lambda \), and then one uses the covariance relation (1.8.1).

We choose \( \sigma = \{ e_1, e_1+e_2 \} \) as a basis of \( \Phi^{eq} \), and write \( z = z_1 e_1 + z_2 e_2 \). Then \( f_\sigma(z) = \frac{1}{z_1(z_1+z_2)} \) is in \( S_H \). If \( v \in \tau_1 \), we have \( A^\Lambda(f_\sigma)(z, v) = \frac{e^{(1, z)}}{(1-e^{(1, z)})(1-e^{(1+1, z)})} \), while if \( v \in \tau_2 \), then \( A^\Lambda(f_\sigma)(z, v) = \frac{1}{(1-e^{(1, z)})(1-e^{(1+1, z)})} \).

For \( v \in V_{reg} \), denote by \( Z^\Lambda(v) : S_H \to M_H \) the map

\[
(Z^\Lambda(v)f)(z) = A^\Lambda(f)(z, v).
\]

This operator is locally constant. We denote its value on \( \tau \) by \( Z^\Lambda(\tau) \). Hence \( (Z^\Lambda(\tau)f)(z) = A^\Lambda(f)(z, v) \) for any choice of \( v \in \tau \).

We now define a piecewise polynomial function of \( v \) associated to a function \( g(z) \) in \( \mathcal{R}_H \). If \( v \in V \) and \( g \in \mathcal{R}_H \), then \( g_v(z) := g(z)e^{(z,v)} \) is a function in \( \mathcal{M}_H \) depending on \( v \). Now suppose \( v \in V_{reg} \), and consider the map \( S_H \to M_H \) which associates to \( f \in S_H \) the function \( g(z)e^{(z,v)}(Z^\Lambda(v)f)(z) \). We project back this function on \( S_H \) using the projector \( \mathbf{R} \). Thus the map

\[
f(z) \mapsto \mathbf{R}\left(g(z)e^{(z,v)}(Z^\Lambda(v)f)(z)\right)
\]

is a map from \( S_H \) to \( S_H \) depending on \( v \). As \( S_H \) is finite dimensional, we can take the trace of this operator, and thus obtain a function of \( v \in V_{reg} \). Let us record this definition.

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Definition 1.14. Let \( g \in \mathcal{R}_H \). Define the function \( P(\mathcal{H}, \Lambda, g) \) on \( V_{reg}(\mathcal{H}, \Lambda) \) by

\[
P(\mathcal{H}, \Lambda, g)(v) := Tr_{S_H}(R_{g, z} Z^\Lambda(v)).
\]

Let us see that \( P(\mathcal{H}, \Lambda, g)(v) \) is a polynomial function of \( v \) on each tope \( \tau \). Indeed, to compute \( P(\mathcal{H}, \Lambda, g)(v) \) using (1.13.1), we have to compute the total residue of functions \( g(z)e^{(z, v)} A^\Lambda(f_i)(z, v) \) with \( f_i \) varying over a basis of \( S_H \). If \( v \in \tau \), then \( A^\Lambda(f_i)(z, v) = Z^\Lambda(\tau) f_i(z) \) is constant in \( v \). So when \( v \) stays in a tope \( \tau \), the dependence of \( g(z)e^{(z, v)} A^\Lambda(f_i)(z, v) = g(z)e^{(z, v)} (Z^\Lambda(\tau) f_i)(z) \) on \( v \) is via \( e^{(z, v)} \), and the map \( R \) involves only the Taylor series of this function up to some order. Thus we have associated to \( g \in \mathcal{R}_H \) (and \( \Lambda \)) a piecewise polynomial function \( P(\mathcal{H}, \Lambda, g) \) on \( V_{reg} \).

It is easy to compare piecewise polynomial functions \( P(\mathcal{H}, \Lambda, g) \) associated to different lattices: Observe that if \( \Lambda^1 \subset \Lambda^2 \), then \( V_{reg}(\mathcal{H}, \Lambda^2) \subset V_{reg}(\mathcal{H}, \Lambda^1) \).

Then, using Lemma 1.9, we have

\[
P(\mathcal{H}, \Lambda^2, g)(v) = |\Lambda^2/\Lambda^1|^{-1} \sum_{\Lambda \in \Lambda^2/\Lambda^1} P(\mathcal{H}, \Lambda^1, g)(v + \lambda). \tag{1.14.1}
\]

Our next aim is to compute the piecewise polynomial function \( P(\mathcal{H}, \Lambda, g) \) using residues. We need more definitions.

An ordered basis of \( \Phi^{eq} \) is a sequence \( [\alpha_1, \alpha_2, \ldots, \alpha_r] \) of elements of \( \Phi^{eq} \) such that the underlying set is in \( \mathfrak{B}(\Phi^{eq}) \). We denote the set of ordered bases of \( \Phi^{eq} \) by \( \mathfrak{B}(\Phi^{eq}) \).

Let \( \overrightarrow{\sigma} = [\alpha_1, \alpha_2, \ldots, \alpha_r] \in \mathfrak{B}(\Phi^{eq}) \). Then, to this data, one associates an iterated residue functional \( \text{Res}^{\overrightarrow{\sigma}} \) on \( \mathcal{R}_H \) as follows. For \( z \in U_C \), let \( z_j = (z, \alpha_j) \). Then a function \( f \) in \( \mathcal{R}_H \) can be expressed as a function \( f(z_1, z_2, \ldots, z_r) \). We define

\[
\text{Res}^{\overrightarrow{\sigma}}(f) := \text{Res}_{z_1=0}(\text{Res}_{z_2=0} \cdots (\text{Res}_{z_r=0} f(z_1, z_2, \ldots, z_r)) \cdots )
\]

Clearly \( \text{Res}^{\overrightarrow{\sigma}}(f_\sigma) = 1 \). Moreover, the functional \( \text{Res}^{\overrightarrow{\sigma}} \) factors through the canonical projection \( R : \mathcal{R}_H \to S_H \), that is, \( \text{Res}^{\overrightarrow{\sigma}} = \text{Res}^{\overrightarrow{\sigma}} R \).

Definition 1.15. A diagonal subset of \( \mathfrak{B}(\Phi^{eq}) \) is a subset \( \overrightarrow{D} \) of \( \mathfrak{B}(\Phi^{eq}) \) such that the set of simple fractions \( f_\sigma, \overrightarrow{\sigma} \in \overrightarrow{D} \), forms a basis of \( S_H \):

\[
S_H = \oplus_{\overrightarrow{\sigma} \in \overrightarrow{D}} C f_\sigma
\]

and the dual basis to the basis \( \{f_\sigma, \overrightarrow{\sigma} \in \overrightarrow{D}\} \) of \( S_H \) is the set of linear forms \( \text{Res}^{\overrightarrow{\sigma}} \), that is, \( \text{Res}^{\overrightarrow{\sigma}}(f_\sigma) = \delta_{\sigma, \overrightarrow{\sigma}}, \) for \( \overrightarrow{\sigma}, \overrightarrow{\sigma} \in \overrightarrow{D} \).

A total order on \( \Phi^{eq} \) allows us to construct the set of Orlik-Solomon bases (see [4]), which provides diagonal basis of \( S_H \). However we will also use some other diagonal subsets.

If \( B : S_H \to M_H \) is an operator, the trace of the operator \( A := RB \) is thus

\[
\text{Tr}(A) := \sum_{\overrightarrow{\sigma} \in \overrightarrow{D}} \text{Res}^{\overrightarrow{\sigma}} B f_\sigma.
\]
Definition 1.16. Let \( g \in \mathcal{R}_H \), \( \tau \) a connected component of \( V_{reg} \), and \( v \in \tau \). We denote by \( P(H, \Lambda, g, \tau)(v) \) the polynomial function on \( V \) such that

\[
P(H, \Lambda, g)(v) = P(H, \Lambda, g, \tau)(v).
\]

We may give a more explicit formula for the polynomial \( P(H, \Lambda, g, \tau)(v) \) using a diagonal subset \( \overrightarrow{D} \).

Proposition 1.17. Let \( g \in \mathcal{M}_H \) and \( \tau \in \mathcal{T}(H, \Lambda) \) be a tope. Let \( \overrightarrow{D} \) be a diagonal subset of \( \overrightarrow{B}(\Phi^{eq}) \). Then

\[
P(H, \Lambda, g, \tau)(v) = \sum_{\sigma \in \overrightarrow{D}} \text{Res}^\mathcal{P} \left( e^{(z,v)} g(z) Z^\Lambda(\tau)(f_\sigma)(z) \right).
\]

Furthermore \( Z^\Lambda(\tau)(f_\sigma)(z) \) is given explicitly by Proposition 1.12. Thus, in principle, the above formula allows us to compute \( P(H, \Lambda, g) \).

It is important to remark that the determination of a diagonal subset \( \overrightarrow{D} \) depends essentially only on the system of hyperplanes \( H \) and not on the choice of \( \Phi^{eq} \). The difficulties in writing an algorithm for \( P(H, \Lambda, g) \) lies in the description of a diagonal subset \( \overrightarrow{D} \), and also for each \( \sigma \in \overrightarrow{D} \), in the computation of \( A^\Lambda(f_\sigma) \). The difficulty of this last computation depends on the lattice \( \Lambda \).

Definition 1.18. Let \( \Phi^{eq} \subset \Lambda \). A basis \( \sigma \in \mathcal{B}(\Phi^{eq}) \) is called unimodular with respect to \( \Lambda \) if \( \Lambda_\sigma = \Lambda \). A set \( \Phi^{eq} \) is called unimodular, if any basis \( \sigma \in \mathcal{B}(\Phi^{eq}) \) is unimodular.

Let \( \sigma = \{ \alpha_1, \alpha_2, \ldots, \alpha_r \} \) be a basis. For \( 1 \leq i \leq r \), the linear form \( v \to c_i^\sigma(v) \) is the coefficient of \( v \) with respect to \( \alpha_i \). Now, consider the function \( \{ t \} = t - [t] \); on each open interval \( \tau = \{ n, n+1 \} \) it coincides with the linear form \( t \mapsto (t-n) \). We express \( v = \sum_{i=1}^r c_i^\sigma(v) \alpha_i \), then \( v - \sum_{i=1}^r [c_i^\sigma(v)] \alpha_i = \sum_{i=1}^r \{ c_i^\sigma(v) \} \alpha_i \) is in \( Q_\sigma \). Thus, if \( \sigma \) is a unimodular basis, the set \( T(\tau, \sigma) \) contains exactly the element \( \lambda = -\sum_{i=1}^r [c_i^\sigma(v)] \alpha_i \) (which depends only on the tope \( \tau \) where \( v \) lies).

Corollary 1.19. Let \( \sigma \) be a unimodular basis in \( \mathcal{B}(\Phi^{eq}) \). Let \( v \in \tau \), and \( \lambda = -\sum_{i=1}^r [c_i^\sigma(v)] \alpha_i \). Then

\[
A^\Lambda(f_\sigma)(z,v) = \frac{e^{(\lambda,z)}}{\prod_{i=1}^r (1 - e^{(\alpha_i,z)})}.
\]

It may happen that even when the system \( \Phi^{eq} \) is not unimodular for \( \Lambda \), we can choose \( \overrightarrow{D} \) to consist of unimodular bases. In particular, using Proposition 1.17, we can give an explicit algorithm for computing the piecewise polynomial function \( P(H, \Lambda, g) \) for classical root systems in the form of a ‘step polynomial’. Let us define what this means.

Definition 1.20. Let \( \overrightarrow{D} \) be a subset of \( \overrightarrow{B}(\Phi^{eq}) \). We denote by \( \text{Step}(\overrightarrow{D}) \) the algebra of functions on \( V \) generated by the piecewise linear functions \( v \to \{ c_i^\sigma(v) \} \) with \( \sigma \) running over \( \overrightarrow{D} \) and \( 1 \leq i \leq r \). An element of the algebra \( \text{Step}(\overrightarrow{D}) \) is called a step polynomial (associated to \( \overrightarrow{D} \)).
It is clear that a step polynomial is a periodic function on $V$, which is expressed by a polynomial formula on each tope.

**Proposition 1.21.** Suppose $\overrightarrow{D}$ is a diagonal subset of $\overrightarrow{B}(\Phi^q)$ consisting of unimodular basis (with respect to $\Lambda$). Then, for $g \in G_\mathcal{H}$, the piecewise polynomial function $P(\mathcal{H}, \Lambda, g)$ belongs to the algebra $\text{Step}(\overrightarrow{D})$.

**Proof.** This is clear, as we have the formula

$$P(\mathcal{H}, \Lambda, g)(v) = \sum_{\mathcal{F} \in \mathcal{B}} \text{Res} \, \overrightarrow{g}(z) e^{\sum_{i=1}^{\infty} \{c_i(v)\}(\alpha_i, z)} \prod_{i=1}^{\infty} \frac{1}{(1 - e^{(\alpha_i, z)})}, \quad (1.21.1)$$

and the dependence on $v$ is through the Taylor series expansion (in $z$) of $e^{\sum_{i=1}^{\infty} \{c_i(v)\}(\alpha_i, z)}$ up to some order. \hfill \Box

1.3. Multiple Bernoulli series

We return to our main object of study: the multiple Bernoulli series.

Let $V$, $\Lambda$ and $\mathcal{H}$ be as before. We denote by $\Gamma \subset U$ the dual lattice to $\Lambda$, and by $\Gamma_{\text{reg}}(\mathcal{H})$ the set $\Gamma \cap U_\mathcal{H}$. If $\gamma \in \Gamma_{\text{reg}}(\mathcal{H})$, a function $g \in R_\mathcal{H}$ is defined on $2\mathcal{I}$.

**Definition 1.22.** If $g \in R_\mathcal{H}$, the generalized function $B(\mathcal{H}, \Lambda, g)(v)$ on $V$ is defined by

$$B(\mathcal{H}, \Lambda, g)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}(\mathcal{H})} g(2i\pi\gamma) e^{2i\pi(v, \gamma)}. \quad (1.22.1)$$

The above series converges in the space of generalized functions on $V$.

We state some obvious properties of $B(\mathcal{H}, \Lambda, g)$, with which we can compare it over commensurable lattices.

**Lemma 1.23.** If $\Lambda^1 \subset \Lambda^2$, then

$$B(\mathcal{H}, \Lambda^2, g)(v) = |\Lambda^2/\Lambda^1|^{-1} \sum_{\lambda \in \Lambda^2/\Lambda^1} B(\mathcal{H}, \Lambda^1, g)(v + \lambda). \quad (1.23.1)$$

If we dilate a lattice $\Lambda$ by $\ell$, and if $g$ is homogeneous of degree $h$, we clearly have

$$B(\mathcal{H}, \ell\Lambda, g)(v) = \ell^{-h} B(\mathcal{H}, \Lambda, g)(\frac{v}{\ell}). \quad (1.23.2)$$

**Definition 1.24.** A generalized function $b$ on $V$ is called piecewise polynomial relative to $\mathcal{H}$ and $\Lambda$ if it is locally $L^1$, and if, for any $\tau$ in $T(\mathcal{H}, \Lambda)$, there exists a polynomial function $b^\tau$ on $V$ such that the restriction of $b$ to $\tau$ coincides with the restriction of the polynomial $b^\tau$ to $\tau$.

As an $L^1$-function is entirely determined by its restriction to $V_{\text{reg}}$, we will not distinguish between piecewise polynomial generalized functions on $V$ and piecewise polynomial functions on $V_{\text{reg}}$ as defined in the preceding section. One should be careful that, the restriction of a piecewise polynomial generalized
function to any tope is polynomial, however, the converse is not true. For example, the δ function of the lattice Λ restricts to 0 on any tope, but is not a piecewise polynomial generalized function, as it is not locally $L^1$.

Any function $f$ in $\mathcal{R}_H$ is of the form $pg$, with $g \in \mathcal{G}_H$ and $p$ a polynomial. Moreover, the function $v \mapsto B(\mathcal{H}, \Lambda, pg)(v)$ is obtained from $B(\mathcal{H}, \Lambda, g)(v)$ by differentiation (in the distribution sense). Thus, the computation of $B(\mathcal{H}, \Lambda, f)$ for $f$ in $\mathcal{R}_H$ can be reduced to that of $B(\mathcal{H}, \Lambda, g)$ for $g$ in $\mathcal{G}_H$. The following proposition follows from calculations in dimension one, Lemma 1.2 and formulae of Lemma 1.23.

**Proposition 1.25.** If $f \in \mathcal{R}_H$, the restriction of $B(\mathcal{H}, \Lambda, f)$ to any tope $\tau$ is given by a polynomial function.

Furthermore, if $f \in \mathcal{G}_H$, the generalized function $B(\mathcal{H}, \Lambda, f)$ is a piecewise polynomial generalized function.

Let us emphasize on the subtle difference between the conditions $f \in \mathcal{R}_H$ and $f \in \mathcal{G}_H$.

Consider $f = 1$ in the one dimensional space $U_C$ and $\mathcal{H} = \{0\}$. The function $f$ is not in $\mathcal{G}_H$. For $v \in V$, $B(\mathcal{H}, \Lambda, f)(v) = \sum_{\eta \neq 0} \epsilon^{2\pi i \eta v} = -1 + \sum_{m \in \mathbb{Z}} \epsilon^{2\pi i \eta m}$, which, on any tope, is the constant function equal to $-1$. However, it has some singular part $\delta_\tau$, and it is not locally $L^1$. In contrast, if $f = \frac{1}{2}$, the generalized function $B(\mathcal{H}, \Lambda, f)(v) = \sum_{\eta \neq 0} \epsilon^{2\pi i \eta v}$ is locally $L^1$ and equal to the piecewise polynomial function $-B(1, \{v\}) = 1/2 - \{v\}$ (see Figure 3).

**Definition 1.26.** Let $f \in \mathcal{R}_H$. Given a tope $\tau$ in $T(\mathcal{H}, \Lambda)$, we denote by $B(\mathcal{H}, \Lambda, f, \tau)$ the polynomial function on $V$ which coincides with $B(\mathcal{H}, \Lambda, f)$ on the tope $\tau$.

Recall the piecewise polynomial function $P(\mathcal{H}, \Lambda, f)$ on $V_{\text{reg}}(\mathcal{H}, \Lambda)$ as given in Definition 1.14.

**Theorem 1.27.** (Szenes) Let $f \in \mathcal{R}_H$. On $V_{\text{reg}}(\mathcal{H}, \Lambda)$, we have

$$B(\mathcal{H}, \Lambda, f) = P(\mathcal{H}, \Lambda, f).$$
For completeness, we give a proof of this theorem in the Appendix.

Our Maple program computes, given data $\mathcal{H}$, $\Lambda$, $f$, where $\mathcal{H}$ is the hyperplane arrangement associated to a classical root system, a piecewise polynomial function on $V$ in terms of step polynomials. Naturally, we can also evaluate this function at any point $v \in V_{\text{reg}}$.

We return to the definition of multiple Bernoulli series as given in the introduction: $V$ is a vector space with a lattice $\Lambda$, and $\Phi$ a list of elements in $\Lambda$. Associated to this data, we defined,

$$B(\Phi, \Lambda)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}(\Phi)} \prod_{\phi \in \Phi} e^{(2i\pi v, \gamma)}(2i\pi \phi, \gamma),$$

where $\Gamma$ is the dual of $\Lambda$, and $\Gamma_{\text{reg}}(\Phi) = \{ \gamma \in \Gamma; (\phi, \gamma) \neq 0 \text{ for all } \phi \in \Phi \}$ is its regular elements.

Consider $\mathcal{H} = \cup_{\phi \in \Phi} \{ \phi = 0 \}$ (some elements of the list $\Phi$ might define the same hyperplane) and $g(z) = 1/\prod_{\phi \in \Phi} (\phi, z)$, then

$$B(\Phi, \Lambda)(v) = B(\mathcal{H}, \Lambda, g)(v).$$

We will also call the functions $B(\mathcal{H}, \Lambda, g)(v)$ multiple Bernoulli series.

2. Classical root systems

Let $G$ be a simple, connected, simply connected, compact Lie group of rank $r$ with maximal torus $T$. We denote the Lie algebra of $T$ and $G$ by $t$ and $\mathfrak{g}$ respectively. Then the complexification $\mathfrak{h} := t_{\mathbb{C}}$ is a Cartan subalgebra of $\mathfrak{g}_{\mathbb{C}}$. Let $R(\mathfrak{g}_{\mathbb{C}}, \mathfrak{h}) \subset \mathfrak{h}^*$ be the set of roots; we denote the root lattice by $Q$ and its dual, the coweight lattice, by $P$. For $\alpha \in R$, $H_\alpha$ denotes the associated coroot; the coroot lattice is denoted by $Q$. The weight lattice is $P = \{ \lambda \in \mathfrak{h}^*; \lambda(H_\alpha) \in \mathbb{Z}, \forall \alpha \in R \}$; a regular weight $\lambda \in P_{\text{reg}}$ is such that $\lambda(H_\alpha) \neq 0$ for all $H_\alpha$. We denote by $\mathfrak{h}_R := \sum_{\alpha} R H_\alpha$ the real span of coroots.

In this section we have $V = \mathfrak{h}_R$, and its dual $\mathfrak{h}_R^*$ is denoted by $U$ as before. We follow the notation of Bourbaki for root data.

2.1. Diagonal subsets

To compute multiple Bernoulli series associated to classical root systems we need to construct explicit diagonal bases for the corresponding $S_{\mathcal{H}}$. Such bases can be constructed by an algorithmic procedure, based on Orlik-Solomon construction [10]. However in some cases one can describe a diagonal subset $\overrightarrow{D}$ of $B(\Phi^{reg})$ whose associated simple fractions form a basis for $S_{\mathcal{H}}$ in a direct way. We now demonstrate this.
2.1.1. The system of type $A_r$

Let $n = r + 1$. We consider $\mathbb{R}^n$ with standard basis $\{e_i\}$; denote the dual basis by $\{e^i\}$. Let $A_r := \{(e_i - e_j); 1 \leq i < j \leq n\}$ be the root system of type $A$ and rank $r$, and $V = \{v = \sum_{i=1}^{n} v_i e^i; \sum_{i=1}^{n} v_i = 0\}$.

Let $z = \sum_{i=1}^{n} z^i e_i$ be in $U_C$ (hence $\sum_{i=1}^{n} z^i = 0$) and let $H_A^r$ be the system of hyperplanes in $U_C$ given by $H_A^r = \cup_{1 \leq i < j \leq n} \{z^i - z^j = 0\}$. We take the set $\Phi^{eq}(A_r) = \{e^i - e^j; 1 \leq i < j \leq n\}$ of positive coroots as equations of $H_A^r$.

One way to find a diagonal basis of $\mathcal{S}_{H_A}$ is as follows.

Let $\Sigma = [e^1 - e^2, e^2 - e^3, \ldots, e^n - e^{n+1}]$ be the set of simple coroots. For a permutation $w$, we denote by $\overrightarrow{\sigma}_w = [e^{w(i)} - e^{w(i+1)}, i = 1, \ldots, r]$. Then $\overrightarrow{\sigma}_w$ is an ordered basis associated to $w$, and the corresponding simple fraction is $f_w(z) := 1 / \prod_{i=1}^{r} (z^{w(i)} - z^{w(i+1)})$.

Let $W_r$ be the subgroup of the Weyl group $\Sigma_{r+1}$ of permutations of $\{e^1, e^2, \ldots, e^{n+1}\}$ leaving the last element $e^{n+1} = e^n$ fixed. Recall the following result (see for example Baldoni-Vergne [2] for a proof).

Proposition 2.1. The set $\overrightarrow{D}_W$ consisting of ordered bases $\overrightarrow{\sigma}_w$ for $w \in W_r$ is a diagonal subset of $\overrightarrow{\mathcal{B}}(\Phi^{eq}(A_r))$.

We use the above basis in our Maple program. We now give another interesting diagonal subset.

Consider a sequence $\overrightarrow{\alpha} = [\alpha_2, \alpha_3, \ldots, \alpha_n]$ where $\alpha_i = e^i - e^j$ with $j < i$. That is, $\alpha_2 = e^2 - e^1$, $\alpha_3 = e^3 - e^2$ or $e^3 - e^1$, $\alpha_4 = e^4 - e^3$, or $e^4 - e^2$, or $e^4 - e^1$, etc. Clearly, $\overrightarrow{\alpha}$ is in $\overrightarrow{\mathcal{B}}(\Phi^{eq}(A_r))$. We call such $\overrightarrow{\alpha}$ a flag basis; there are $r!$ such sequences $\overrightarrow{\alpha}$.

Lemma 2.2. The set $\overrightarrow{D}(A_r)$ consisting of flag bases is a diagonal subset of $\overrightarrow{\mathcal{B}}(\Phi^{eq}(A_r))$.

We only need to prove that if $\overrightarrow{\alpha}$ and $\overrightarrow{\beta}$ are two flag bases, then $\text{Res} \overrightarrow{\alpha} f_r = 0$ unless $\overrightarrow{\alpha} = \overrightarrow{\beta}$. But this is evident.

2.1.2. Systems of type $B_r$ or $C_r$

We consider $V = \mathbb{R}^r$ with standard basis $\{e^i\}$. Let $B_r = [\pm e^i, \pm(e^i \pm e^j), 1 \leq i \leq r, 1 \leq i < j \leq r]$ be the root system of type $B$ and rank $r$.

Let $C_r = [\pm 2e^i, \pm(e^i \pm e^j), 1 \leq i \leq r, 1 \leq i < j \leq r]$ be the root system of type $C$ and rank $r$.

As roots of the systems of type $B$ and $C$ are proportional, the system of hyperplanes in $U = h^*_B$ defined by coroots of $B$ and $C$ are the same, and we denote that system (and the corresponding complex arrangement) by $H_{BC}^r$. More precisely, let $z = \sum_{i=1}^{r} z^i e_i$ in $U_C$, then the system of hyperplanes $H_{BC}^r$ in $U_C$ is given by $H_{BC}^r = \cup_{1 \leq i < j \leq r} \{z^i \pm z^j = 0\} \cup \cup_{1 \leq i \leq r} \{z^i = 0\}$.

We take the set $\Phi^{eq}(BC_r) = \cup_{1 \leq i < j \leq r} \{e^i \pm e^j = 0\} \cup \cup_{1 \leq i \leq r} \{e^i = 0\}$ as equations of $H_{BC}^r$.

We now define a flag basis $\overrightarrow{\alpha}$ of $\Phi^{eq}(BC_r)$. This is a basis of the form $\overrightarrow{\alpha} = [\alpha_1, \alpha_2, \ldots, \alpha_r]$ of $r$ elements of $\Phi^{eq}(BC_r)$ so that $\alpha_i = e^i$, or $e^i - e^j$ or
$e^i + e^j$ with $j < i$. That is, $\alpha_1 = e^1$, $\alpha_2 = e^2$ or $e^2 - e^1$, or $e^2 + e^1$, $\alpha_3 = e^3$ or $e^3 - e^2$, or $e^3 + e^2$, or $e^3 - e^1$, or $e^3 + e^1$, etc. Clearly, there are $1 \cdot 3 \cdot 5 \cdots (2r - 1)$ such sequences $\mathcal{F}$.

**Lemma 2.3.** The set $\mathcal{B}(BC_r)$ consisting of flag bases is a diagonal subset of $\mathcal{B}(\Phi^o(BC_r))$.

**Proof.** We first prove, by induction on $r$, that simple fractions $f_b$ associated to a flag basis $b$ generate $\mathcal{S}_{H^D}$. We use the identities

$$
\frac{1}{(x_r - x_i) (x_r + x_i)} = \frac{1}{(x_r + x_i)} \frac{1}{2x_r} + \frac{1}{(x_r - x_i)} \frac{1}{2x_r},
$$

$$
\frac{1}{x_r(x_r + x_i)} = \frac{1}{(x_r + x_i) x_i} + \frac{1}{x_r x_i} - \frac{1}{(x_r - x_i) x_i} - \frac{1}{x_r x_i},
$$

to reduce to the case where a simple fraction $f_b$ contains a linear form of type $e^r$, or $e^r + e^i$ or $e^r - e^i$ in the denominator, but not any two at the same time.

Then, by induction on $r$, we see that the simple fractions $f_b$ associated to flag basis $b$ generates the space $\mathcal{S}_{H^D}$. The dual property on the elements of $\mathcal{B}(BC_r)$ is evident.

**Remark 2.4.** Although the system $\Phi^o(BC_r)$ is not unimodular for the lattice $\Lambda = \oplus \mathbb{Z}e^i$, we see that any $\mathcal{F}$ in the set $\mathcal{B}(BC_r)$ above is unimodular, so that the computation of $Z^\Lambda(\tau)(f_r)$ is easy.

### 2.1.3. The system of type $D_r$

We consider $V = \mathbb{R}^r$ with standard basis $\{e^i\}$. Let $D_r = [\pm (e_i \pm e_j); 1 \leq i < j \leq r]$ be the root system of type $D$ and rank $r$. Let $z = \sum_{i=1}^{r} z^i e_i$ in $U_\mathbb{C}$. We consider the system of hyperplanes in $U_\mathbb{C}$

$$
\mathcal{H}^D_r = \bigcup_{1 \leq i < j \leq r} \{z^i \pm z^j = 0\}.
$$

The dimension of $\mathcal{S}_{H^D}$ is known to be $1 \cdot 3 \cdot 5 \cdots (2r - 3)(r - 1)$. However, we did not find a nice diagonal basis for $\mathcal{S}_{H^D}$. We proceed as follows: The set $\mathcal{U}_{\mathcal{H}^D_r}$ of regular elements for $\mathcal{H}^D_r$ contains $\mathcal{U}_{H^D}$. Indeed, for any $z$ in $\mathcal{U}_{\mathcal{H}^D_r}$, we have $z^i \pm z^j \neq 0$, but $z^i$ may equal zero. We define the set

$$
U_{k, r} := \{z^k = 0, z^i \pm z^j \neq 0 \text{ for } 1 \leq i < j \leq r \text{ and } z^i \neq 0 \text{ for } 1 \leq i \leq r, i \neq k\}.
$$

Then, the following disjoint decomposition $U_{\mathcal{H}^D} = \mathcal{U}_{H^D} \bigcup_{k=1}^{r} U_{k, r}$ holds. The set $U_{k, r}$ is clearly isomorphic to the set $\mathcal{U}_{k, r}$ in rank $r - 1$ via the map $i_k$ which inserts a zero coordinate in position $k$, and hence,

$$
U_{\mathcal{H}^D} = \mathcal{U}_{H^D} \bigcup_{k=1}^{r} i_k(U_{\mathcal{H}^D}). \tag{2.4.1}
$$

The above decomposition allows us to reduce calculations in systems of type $D$ to those of systems of type $B$ or $C$. 

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2.2. Calculations of multiple Bernoulli series for type A

We use the same notation as in Section 2.1.1.

Let \( Q_A \subset U \) be the root lattice generated by \( A_r \), and \( P_A \subset U \) be the weight lattice. Then \( P_A \) is generated by \( Q_A \) and \( e_1 - \frac{1}{r+1}(e_1 + e_2 + \cdots + e_{r+1}) \). The cardinality of \( P_A/Q_A \) is \( r+1 \).

Let \( \Gamma \) be a lattice such that \( Q_A \subset \Gamma \subset P_A \). We denote by \( \Gamma_{\text{reg}} = \Gamma \cap U_H^A \) the set of regular elements in \( \Gamma \). Let \( \Lambda \subset V \) be the dual lattice to \( \Gamma \), and let \( s = [s_\alpha] \) be a list of exponents. Define

\[
g^A_s(z) = \prod_{\alpha > 0} \frac{1}{(H_\alpha, z)^{s_\alpha}},
\]

where the set \( \{H_\alpha, \alpha > 0\} \) is the set of positive coroots \( \Phi^q(A_r) \). If \( v \in V \),

\[
B(H^A_r, \Lambda, g^A_s)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}} \prod_{\alpha > 0} \frac{e^{2\pi i (v, \gamma)}}{(2\pi i (H_\alpha, \gamma))^{s_\alpha}}.
\]

If we use the diagonal basis \( \mathcal{D}_W \) for \( \Phi^q(A_r) \) as defined in Proposition 2.1, then it consists of elements \( [e^{w(1)} - e^{w(2)}, \ldots, e^{w(r)} - e^{w(r+1)}] \) where \( w \) is an element of \( W_r \). Thus if we express \( v = \sum_{i=1}^r v_i(e^i - e^{r+1}) \), the algebra \( \text{Step}(\mathcal{D}_W) \) consists of functions \( \{\sum_i v_i\} \) where \( I \) runs over subsets of \( \{1, 2, \ldots, r\} \).

We now discuss two simple cases, where \( \Gamma \) is either the weight lattice \( P_A \), or the root lattice \( Q_A \).

2.2.1. Bernoulli series for the weight lattice

The dual of the weight lattice \( P_A \) is the coroot lattice \( Q_A \) generated by simple coroots \( H_\alpha \), and the system \( \Phi^q(A_r) \) of equations (the positive coroots) is unimodular with respect to \( Q_A \). Thus \( B(H^A_r, Q_A, g^A_s)(v) \) is a piecewise polynomial function of degree \( \sum_\alpha s_\alpha \) and lies in the algebra \( \text{Step}(\mathcal{D}_W) \).

Our program then gives \( B(H^A_r, Q_A, g^A_s)(v) \) as a polynomial expression in \( \{\sum_i v_i\} \). It also computes numerically the value of this function at any point \( v \).

Example 2.5. Consider the root system of type \( A_2 \). For \( s = [1,1,1] \),

\[
B(H^A_2, Q_A, g^A_s)(v) = \sum_{m,n,m+n \neq 0} \frac{e^{2\pi imv_1 - 2\pi imv_3}}{(2\pi i m)(2\pi i n)(2\pi i (m+n))},
\]

where \( v = v_1 e^1 + v_2 e^2 + v_3 e^3 \) with \( v_1 + v_2 + v_3 = 0 \). Denoting the fractional part of \( t \) with \( \{t\} \in [0,1] \), we obtain that \( P(v_1, v_2, v_3) := B(H^A_2, Q_A, g^A_s)(v) \) is equal to

\[
\frac{1}{6}(\{v_2\} - \{v_1\})(\{v_1\}^2 - 3\{v_1 + v_2\} \{v_1\} + 3\{v_1\} \{v_1\} + 3\{v_1 + v_2\} - 1 - 3\{v_1 + v_2\} \{v_2\} + \{v_2\}^2).
\]

We remark that the series (2.5.1) is not absolutely convergent, but the sum has a meaning and is a piecewise polynomial function.
Let us give some numerical examples.
Consider \(A_2\) with \(s = [10, 10, 10]\), \(v_1 = v_2 = 0\). Then, \(B(H^A, \tilde{Q}_A, g^A_0)(0)\) is
\[
\sum_{m,n} \frac{1}{(2\pi m)^{10}(2\pi n)^{10}(2\pi (m + n))^{10}} = \frac{2773097}{417467193212109927669143961600000000}
\]
Consider \(A_4\). We list the exponents with respect to the following order on the roots \([e_1 - e_2, e_1 - e_3, e_1 - e_4, e_2 - e_3, e_2 - e_4, e_2 - e_5, e_3 - e_4, e_3 - e_5, e_4 - e_5]\).
For \(s = [6, 6, 6, 4, 2, 2, 2, 2, 2]\) and \(v = [0, 0, 0, 0, 0]\),
\[
B(H^A, \tilde{Q}_A, g^A_0)(0) = \frac{1}{(2\pi)^{10}} \times \sum_{l=1}^r \frac{1}{20814165388976983019020695652962140160000000000}
\]
while for \(s = [4, 4, 4, 4, 4, 4, 4, 4, 4]\) and \(v = [0, 0, 0, 0, 0]\), we obtain
\[
B(H^A, \tilde{Q}_A, g^A_0)(0) = \frac{3998447009863}{19318834119102098604968210835862034086625280000000000000}
\]

2.2.2. Bernoulli series for the root lattice
Let \(\xi = \sum_{j=1}^r (e^j - e^{-j})\). Then a system of representatives for \(\tilde{P}_A/\tilde{Q}_A\) consists of the elements \(\{\lambda_j = \frac{1}{r+1} \xi 0 \leq j \leq r\}\). Using Formula (1.23.1),
\[
B(H^A, \tilde{P}_A, g^A_0)(v) = \frac{1}{r+1} \sum_{j=0}^r B(H^A, \tilde{Q}_A, g^A_0)(v + \lambda_j).
\]
Hence, we obtain an expression for \(B(H^A, \tilde{P}_A, g^A_0)\) in terms of the functions \(\{(\sum_{l=1}^r v_l) + c/(r+1)\}\) where \(c\) are integers between 0 and \(r\).

Example 2.6. With the notation of Example 2.5, we now compute \(B(H^A, \tilde{P}_A, g^A_0)(v)\) for \(v = v_1e^1 + v_2e^2 + v_3e^3\) with \(v_1 + v_2 + v_3 = 0\). We express \(v = v_1(e^1 - e^2) - v_3(e^2 - e^3)\). For exponents \(s = [1, 1, 1]\),
\[
B(H^A, \tilde{P}_A, g^A_0)(v) = \sum_{m,n \in \mathbb{Z}} \frac{e^{2\pi i m (n_1 - n_2) + 2\pi i n (v_2 - v_3)}}{(2\pi (2m - n)(2\pi (2n - m))(2\pi (m + n))}
\]
\[
= \frac{1}{3} \left( P(v_1, v_2, v_3) + P(v_1 + \frac{1}{3}, v_2 + \frac{1}{3}, v_3 - \frac{2}{3}) + P(v_1 + \frac{2}{3}, v_2 + \frac{2}{3}, v_3 - \frac{4}{3}) \right),
\]
where \(P\) is the piecewise polynomial function given in Equation (2.5.2).
2.3. Calculation of multiple Bernoulli series for types $B$ and $C$

We use the same notation as in Section 2.1.2.

We now consider $H_r^{BC} = \cup_{1 \leq i \leq r} \{z^i = 0\} \cup \cup_{1 \leq i < j \leq r} \{z^i \pm z^j = 0\}$, a system of hyperplanes in $U_C$.

Let $\Lambda$ be a lattice commensurable with $\oplus \mathbb{Z} e^i$, with dual lattice $\Gamma$. Denote simply by $\Gamma_{\text{reg}} = \Gamma_{\text{reg}}(H_r^{BC})$. If $g \in R_{H^{BC}}$,

$$B(H_r^{BC}, \Lambda, g)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}} g(2i\pi\gamma)e^{2i\pi\langle v,\gamma \rangle}.$$  \hspace{1cm} (2.6.1)

2.3.1. Root system $C_r$

Let $P_C$ be the weight lattice of the root system $C_r$. We thus have the coroot lattice $Q_C = \oplus_{i=1}^{r} \mathbb{Z} e^j$. Let $s = [s_\alpha]$ be a list of exponents and let

$$g^C_s(z) = \frac{1}{\prod_{\alpha > 0}(H_\alpha, z)^{s_\alpha}}.$$

Here $\{H_\alpha, \alpha > 0\}$ are positive coroots of the system $C_r$, which are explicitly $\{e^i, 1 \leq i \leq r, (e^i \pm e^j), 1 \leq i < j \leq r\}$. Clearly, the function $g^C_s$ belongs to $R_{H^{BC}}$. If $v \in V$,

$$B(H_r^{BC}, Q_C, g^C_s)(v) = \sum_{\gamma \in (P_C)_{\text{reg}}} \frac{e^{2i\pi\langle v,\gamma \rangle}}{\prod_{\alpha > 0}(2i\pi(H_\alpha, \gamma))^{s_\alpha}}.$$

The function $B(H_r^{BC}, Q_C, g^C_s)$ is a piecewise polynomial function on $V$ of degree $\sum s_\alpha$. We use the diagonal basis constructed in Section 2.1.2 to compute it.

Let us now compute the example given in the introduction, which corresponds to $C_2$ with exponents $s = [2, 1, 1, 1]$ ordered in accordance with the order $[2e_1, 2e_2, e_1 + e_2, e_1 - e_2]$ of positive roots (so that $[e^1, e^2, e^1 + e^2, e^1 - e^2]$ is the corresponding order in positive coroots). Express $v = v_1 e^1 + v_2 e^2$, then

$$B(H_2^{BC}, Q_C, g^C_s)(v) = \sum_{m,n} e^{2i\pi v_1 m + 2i\pi v_2 n} (2i\pi m)^2 (2i\pi n)^2 (2i\pi(m + n))^2 (2i\pi(m - n))^2.$$

This piecewise polynomial function $Q(v_1, v_2) := B(H_2^{BC}, Q_C, g^C_s)(v)$ is given by

$$Q(v_1, v_2) = -\frac{1}{160} (-v_2 + v_1)^5 - \frac{1}{48} v_1^2 + \frac{1}{24} \{v_2 + v_1\}^3 \{v_2\} - \frac{1}{48} \{v_2 + v_1\}^4 \{v_2\} + \frac{1}{24} v_1^3 - \frac{1}{48} \{v_2 + v_1\}^2 \{v_2\} - \frac{1}{960} \{v_2 + v_1\}^2 \{v_2\} + \frac{1}{96} \{v_2 + v_1\}^3 \{v_2\} - \frac{1}{12} \{v_2 + v_1\}^4 \{v_2\} + \frac{5}{192} \{v_2 + v_1\}^5 \{v_2\} + \frac{1}{24} \{v_2 + v_1\}^2 \{v_2\} - \frac{1}{12} \{v_2 + v_1\}^3 \{v_2\} + \frac{1}{24} \{v_2 + v_1\}^4 \{v_2\} + \frac{1}{160} \{v_2 + v_1\}^5 \{v_2\} + \frac{1}{24} \{v_2 + v_1\}^3 \{v_2\} - \frac{1}{48} \{v_2 + v_1\}^2 \{v_2\}.$$  \hspace{1cm} (2.6.2)
Let us demonstrate what happens on a tope. Figure 2 depicts topes associated to the pair $\Phi_\alpha(BC_2) = \{e^1, e^2, e^1 + e^2, e^1 - e^2\}$ and $\Lambda = Ze^1 \oplus Ze^2$. For example, on $\tau_2 = \{v_1 > 0, v_2 > 0, v_1 > v_2, v_1 + v_2 < 1\}$, the piecewise polynomial function $B(\mathcal{H}_r^{BC}, \tilde{Q}_C, g_C^q)(v)$ coincides with the polynomial

$$Q_{\tau_2}(v_1, v_2) = \frac{1}{8} \left( -\frac{1}{6} v_2 + \frac{1}{2} v_1^2 v_2 - v_1^3 v_2 + \frac{1}{6} v_1^2 - v_1 v_2^2 + v_1 v_3^2 + v_1 v_2^2 \right)$$

$$- \frac{1}{6} v_2^3 + \frac{1}{6} v_4^2 + \frac{1}{2} v_4 v_2 - v_1 v_2 v_3^2 - \frac{7}{30} v_2^5 \right) \quad (2.6.3)$$

We give some more numerical examples with different exponents. For example, we may compute with exponents $s = [s_1, s_2, s_3, s_4]$ corresponding to the order $[2e_1, 2e_2, e_1 + e_2, e_1 - e_2]$ of roots, and $v = [v_1, v_2]$. Then,

$$B(\mathcal{H}_r^{BC}, \tilde{Q}_C, g_C^q)(v_1, v_2) = \sum_{m,n} e^{2\pi i m v_1 + 2\pi i n v_2}$$

$$= \left\{ \begin{array}{ll}
810650230 & \text{if } s = [2,2,1,1] \text{ and } v = [1/5, 1/19] \\
132316540 & \text{if } s = [2,3,4,5] \text{ and } v = [1/7, 1/17]
\end{array} \right.$$
For example, for $B_2$, we compute for $v = v_1 e^1 + v_2 e^2$ and exponents $s = [2,1,1,1]$ ordered with respect to the order $[e_1 - e_2, e_1 + e_2, e_1]$ of roots,

$$(2\pi)^5 \mathcal{B}(\mathcal{H}_{2}^{BC}, \tilde{Q}_B, g_s^B)(v) = \sum_{m_1, m_2}^\prime \frac{e^{2\pi((m_1+1/2)m_2)v_1+1/2m_2v_2}}{m_1^2m_2(2m_1 + m_2)(m_2 + m_1)}$$

where the symbol $\sum^\prime$ means we sum over the integers $m_1, m_2$ with $(2m_1 + m_2)(m_2 + m_1)m_2m_1 \neq 0$. We obtain

$$\mathcal{B}(\mathcal{H}_{2}^{BC}, \tilde{Q}_B, g_s^B)(v) = 2 \left( Q\left(\frac{v_1}{2}, \frac{v_2}{2}\right) + Q\left(\frac{v_1 + 1}{2}, \frac{v_1}{2}\right) \right)$$

where $Q = \mathcal{B}(\mathcal{H}_{2}^{BC}, \tilde{Q}_C, g_s^C)$ is given in Equation (2.6.2).

In particular, for $u = [1/15, 1/30]$ we obtain

$$\mathcal{B}(\mathcal{H}_{2}^{BC}, \tilde{Q}_B, g_s^B)(u) = \frac{-276037}{5832000000}.$$ 

For $B_3$, we compute for $v = v_1 e^1 + v_2 e^2 + v_3 e^3$ and $s = [1,1,1,1,1,1,1,1]$:

$$(2\pi)^9 \mathcal{B}(\mathcal{H}_{3}^{BC}, \tilde{Q}_B, g_s^B)(v) = \frac{e^{2\pi((m_1+1/2)m_2)v_1+1/2m_2v_2}}{m_1^3m_2(2m_1 + m_2)(2m_2 + m_3)m_1m_2m_3(m_1 + m_2 + m_3)(m_1 + m_2 + m_3)m_2(m_2 + m_3)}$$

We obtain

$$\mathcal{B}(\mathcal{H}_{3}^{BC}, \tilde{Q}_B, g_s^B)(v) = 2^4 \left( S\left(\frac{v_1}{2}, \frac{v_2}{2}, \frac{v_3}{2}\right) + S\left(\frac{v_1 + 1}{2}, \frac{v_2 + 1}{2}, \frac{v_3}{2}\right) + S\left(\frac{v_1}{2}, \frac{v_2 + 1}{2}, \frac{v_3 + 1}{2}\right) + S\left(\frac{v_1 + 1}{2}, \frac{v_2}{2}, \frac{v_3 + 1}{2}\right) \right)$$

where $S = \mathcal{B}(\mathcal{H}_{3}^{BC}, \tilde{Q}_C, g_s^C)$ is a piecewise polynomial that is too long to be included here.

### 2.4. Calculation of multiple Bernoulli series for type D

We follow the same notation as in Section 2.1.3.

Recall the system of hyperplanes $\mathcal{H}_{D}^r = \bigcup_{i,j} \{z^i \pm z^j = 0, 1 \leq i < j \leq r\}$. Let $s = [s_i]$ be a list of exponents; the ordering of elements in the list $s$ is taken to match the following ordering $[e_1 - e_2, e_1 - e_3, \ldots, e_1 - e_r, e_2 - e_3, \ldots, e_1 + e_2, \ldots, e_{r-1} + e_r]$ of positive roots of the system $D_r$. We define

$$g_s^D(z) = \frac{1}{\prod_{\alpha > 0} (H_{\alpha}, z)^{s_\alpha}},$$

where $\{H_{\alpha}, \alpha > 0\}$ are positive coroots of $D_r$.

We embed the list of roots of $D_r$ in to the list of roots of $B_r$ by writing the short roots $e_i$ of $B_r$ at the very end of the list. We denote by $s = [s_0, 0, \ldots, 0]$ the list obtained from $s$ by adjoining $r$ zeros to its end. Then, by construction, we have $g_s^D(z) = g_s^B(z)$.

We now associate to the list $s$ a list of exponents $s_r$ for the system $B_{r-1}$. In $s$ we eliminate the position corresponding to the roots $e_i \pm e_k$ for $i < k$, and
\( e_k \pm e_i \) for \( i > k \). Then we assign the value \( s_{e_i+e_k} + s_{e_i-e_k} \) to the exponent corresponding to root \( e_i \) of \( B_{r-1} \) for \( i < k \), similarly we assign the value \( s_{e_k+e_i} + s_{e_k-e_i} \) to the exponent corresponding to the root \( e_i \) of \( B_{r-1} \) for \( i > k \).

We also let \( i_k(v) \) to be the vector with \( r-1 \) coordinates obtained from \( v = \sum_{i=1}^r v_i e_i \) by putting \( v_k = 0 \).

Let \( \Gamma = P_D \) be the weight lattice of \( D \) and \( \tilde{Q}_D \) the dual lattice generated by the coroots. Since \( P_D \) is the weight lattice of the simply connected group \( \text{Spin}(2r) \), \( \gamma = \sum_{i=1}^r \gamma_i e_i \) is in \( P_D \) if \( \gamma_i \pm \gamma_j \in \mathbb{Z} \) and \( P_D = P_B \). Consider the intersection of \( P_D \) with the hyperplane \( z^k = 0 \). Then, we see that this intersection is isomorphic to the weight lattice of a system \( C_{r-1,k} \) of type \( C \), rank \( r-1 \), embedded in \( C \) of rank \( r \) with simple roots \( \{ e_1 - e_2, e_2 - e_3, \ldots, e_{k-1} - e_{k+1}, e_{k+1} - e_{k+2}, \ldots, e_r \} \).

Using the decomposition (2.4.1), we decompose the set of regular elements of the lattice \( P_D \) as a disjoint union of the set of regular elements of the lattice \( P_B \) and the set of regular elements of the lattice \( P_C \) of rank \( r-1 \). In particular, if \( \gamma \in (P_D)_{reg} \) and \( \gamma_k = 0 \), then

\[
g^D_\alpha(\gamma) = \prod_{\gamma_i \pm \gamma_j \neq 0, \gamma_k = 0} \frac{1}{(\gamma_i - \gamma_j)^{s_{\gamma_i, \gamma_j}}(\gamma_i + \gamma_j)^{s_{\gamma_i, \gamma_j}}} = c_k g^C_\alpha(i_k(\gamma))
\]

with \( c_k = (-1)^{\sum_{i=k+1}^r s_{\gamma_i, \gamma_j}} \). In particular, if \( s = [m, \ldots, m] \), then \( c_k = (-1)^{(r-k)m} \).

Thus, we can compute multiple Bernoulli series for the system of type \( D_r \) by using computations for types \( B_r \) and \( C_{r-1} \) with appropriate exponents. More explicitly,

\[
B(\mathcal{H}^D_r, \tilde{Q}_D, g^D_\alpha)(v) = \sum_{\gamma \in (P_D)_{reg}} \prod_{\alpha > 0} \frac{e^{2\pi (v, \gamma)}}{(2\pi (H^\alpha, \gamma))^\alpha} g^C_\alpha(\gamma) = B(\mathcal{H}^B_r, \tilde{Q}_B, g^B_\alpha)(v) + \sum_{k=1}^r c_k B(\mathcal{H}^B_{r-1}, \tilde{Q}_{C_{r-1,k}}, g^C_\alpha)(i_k(v)).
\]

3. Witten formula for volumes of moduli spaces of flat connections on surfaces

As in Section 2, let \( G \) be a simple, connected, simply connected, compact Lie group of rank \( r \) with maximal torus \( T \). For \( g_1, g_2 \in G \), we denote by \( [g_1, g_2] = g_1g_2g_1^{-1}g_2^{-1} \) the commutator of \( g_1 \) and \( g_2 \). Let \( \Sigma \) be a compact connected oriented surface of genus \( g \) and let \( p := \bigcup p_j \) be a set of \( s \) points on \( \Sigma \). Let \( \mathcal{C} := \{ C_j \} \) be a set of \( s \) conjugacy classes in \( G \). We consider the representation variety

\[
\mathcal{M}(G, g, s, \mathcal{C}) := \{ (a, c) \in C^{2g} \times \mathcal{C}; \prod_{i=1}^g [a_{2i-1}, a_{2i}] = \prod_{j=1}^s c_j \}/G.
\]

If the adjoint orbits \( \mathcal{C}_j \) are generic, \( \mathcal{M}(G, g, s, \mathcal{C}) \) is an orbifold of real dimension \((2g-2) \dim G + s \dim G/T \). It parameterizes the set of flat \( G \)-valued connections
on $\Sigma - p$, with holonomy around $p_j$ belonging to the conjugacy class $C_j$ modulo gauge equivalence. As shown by Atiyah-Bott [1], once a $G$-invariant inner product on $\mathfrak{g}$ is chosen, the manifold $\mathcal{M}(G, g, s, C)$ carries a natural symplectic form, and thus a natural volume form. E. Witten gave a formula for the volume of $\mathcal{M}(G, g, s, C)$ that we recall.

Let $R^+$ be a choice of positive roots; denote the highest root of $R$ by $\rho$. Let $\mathfrak{h}_+ := \{ h \in \mathfrak{h}_R; \alpha(h) \geq 0 \text{ for all } \alpha \in R^+ \}$ be the positive chamber (closed) in $\mathfrak{h}_R$, and $\mathfrak{A} := \{ h \in \mathfrak{h}_+; \theta(h) \leq 1 \}$ be the fundamental alcove. An element of $\mathfrak{A}$ is said to be regular if it lies strictly inside the alcove. Let $W = W(\mathfrak{g}_C, \mathfrak{h})$ be the Weyl group (identified with $N_G(T)/T$).

We now give the Witten formula. Let $a = \{ a_1, a_2, \ldots, a_s \}$ be a set of regular elements in $\mathfrak{A}$. Let $C_j$ be the adjoint orbit of $\exp(a_j)$; we denote the collection of orbits $C_j$ by $C$. Consider the function on $h$ given by

$$N_a(\lambda) = \prod_{j=1}^s \sum_{w \in W} \varepsilon(w) e^{i w a_j \lambda}.$$

Let $\Phi = \Phi(G)$ be the list of positive coroots $H_a$. Define

$$W(\Phi(G), P, g, s)(a) := \sum_{\gamma \in P^{+ s}} \frac{N_a(2i\pi \gamma)}{\prod_{H_a \in \Phi} (2i\pi \langle H_a, \gamma \rangle)^{2g - 2 + s}}.$$

The above expression is always meaningful as a generalized function of the parameters $a_j$. If $s = 0$, this formula has to be understood as

$$W(\Phi(G), P, g) = \sum_{\gamma \in P^{+ s}} \frac{1}{\prod_{H_a \in \Phi} (2i\pi \langle H_a, \gamma \rangle)^{2g - 2}}$$

which is meaningful if $g \geq 2$.

Interchanging the sum and the product, $N_a(\lambda)$ may be expressed as

$$N_a(\lambda) = \sum_{(w_1, w_2, \ldots, w_s) \in W^s} \prod_{j=1}^s \varepsilon(w_j) e^{\sum_{i=1}^s (w_j a_j \lambda)}.$$

Hence the function $W(\Phi(G), P, g, s)(a)$ can be expressed as a sum over $W^s$ with signs of Bernoulli series $B(\Phi_{2g - 2 + s}, Q)(\sum_j w_j a_j)$. Here, as before, $\Phi_{2g - 2 + s}$ means that each coroot in $\Phi$ is taken with multiplicity $2g - 2 + s$. As is well known, the series $W(\Phi(G), P, g, s)(a)$ computes the symplectic volume of $\mathcal{M}(G, g, s, C)$ up to a scalar factor, which we will give in the next section.

Let us now recall the normalization of the volume as the limit of the Verlinde formula. To demonstrate this we need some more notation.

Let $(|)$ denote the $G$-invariant symmetric form on $\mathfrak{g}_C$ normalized such that $(H_0 | H_0) = 2$. We will use the same notation for the restricted form on $\mathfrak{h}$, and the induced form on $\mathfrak{h}^*$. We call $(|)$ the basic invariant form. It is positive definite on $\mathfrak{h}_R$, and negative definite on $t$. 

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Let \( \tilde{h} := \rho(H_0) + 1 \) be the dual Coxeter number, where \( \rho \) is the half sum of positive roots. Let \( Q_{\text{long}} \subset Q \) be the lattice spanned by long roots. The basic invariant form identifies \( \mathfrak{h}_R \) and \( \mathfrak{h}^*_R \); under this isomorphism the coroot lattice \( Q \) is identified to \( Q_{\text{long}} \). Let \( q \) be the index of \( Q_{\text{long}} \) in \( Q \), and let \( f \) be the index of \( Q \) in \( P \). The center of \( G \) is denoted by \( Z = Z(G) \).

For a positive integer \( \ell \), define the set

\[
P_{\ell} := \{ \mu \in P \cap \mathfrak{h}^*_R; \mu(H_0) \leq \ell \}.
\]

An element of \( P_{\ell} \) is said to be a weight of level \( \ell \). We denote by \( P_{\ell}^{\text{reg}} \) the subset of \( P_{\ell} \) consisting of elements \( \mu \) satisfying \( \mu(H_0) < \ell \) and \( \mu(H_\alpha) > 0 \) for any simple root \( \alpha \). By definition of \( \tilde{h} \), there is a bijection between sets \( P_{\ell} \) and \( P_{\ell + \tilde{h}} \) via \( \mu \mapsto \mu + \rho \).

Consider the maximal torus \( T \) of \( G \) with Lie algebra \( t \). If \( t = \exp X \in T \), with \( X \in t \), and \( \alpha \) is a root (which takes imaginary values on \( t \)), we denote by \( e^\alpha(t) = e^{(\alpha, X)} \). Let \( \Delta(t) = \prod_{\alpha \in R}(e^{\alpha}(t) - 1) \). An element \( t \) of \( T \) is said to be regular if \( \Delta(t) \neq 0 \). Denote by \( T_{t} \) the subgroup of elements \( t \) of \( T \) such that \( e^\alpha(t) \) is \( \ell + \tilde{h} \) root of unity for each long root \( \alpha \). We denote the set of regular elements in \( T_{t} \) by \( T_{\ell}^{\text{reg}} \).

We now give the Verlinde formula.

Consider a set \( \Delta = \{ \lambda_1, \lambda_2, \ldots, \lambda_s \} \) with \( \lambda_i \in P_{\ell} \). Then to this collection \( \Delta \), the group \( G \), and a nonnegative integer \( g \), is associated a vector space \( V(G, g; s, \Delta, \ell) \) (see [15]), called the space of conformal blocks, whose dimension is given by the Verlinde formula \( V(G, \Delta, g, \ell) \):

\[
V(G, \Delta, g, \ell) = (fg)^{q-1}(\ell + \tilde{h})^{r(q-1)} \sum_{t \in T_{\ell}^{\text{reg}}/W} \frac{\chi_{V(\Delta)}(t)}{\Delta(t)^{q-1}}.
\]

Above \( r \) is the rank of \( G \), \( V(\Delta) = V_{\lambda_1} \otimes V_{\lambda_2} \otimes \cdots \otimes V_{\lambda_s} \) where \( V_{\lambda_i} \) denotes the simple \( g \) module with highest weight \( \lambda_i \), and \( \chi_{V_\lambda} \) denotes the character of \( V_{\lambda} \). By Weyl character formula \( \chi_{V_\lambda} = J(e^{\lambda+\rho})/J(e^\rho) \) where \( J(e^\rho) = \sum_{w \in W} \varepsilon(w)e^{w\rho} \).

We remark that if \( \sum_{i=1}^{s} \lambda_i \) is not in the root lattice, then \( V(G, \Delta, g, \ell) \) is zero.

Under the isomorphism given by the basic invariant form, an element \( a \) lying in \( \mathfrak{a} \subset \mathfrak{h}_R \) defines an element \( \tilde{a} \) of \( \mathfrak{b}^*_R \). We now consider a collection \( \{a_1, a_2, \ldots, a_s\} \) of rational elements in \( \mathfrak{a} \), that is, each \( a_j \) lies in the dense subset \( \mathfrak{a} \cap (Q \otimes \mathbb{Q}) \subset \mathfrak{a} \). We may choose \( \ell \) large enough so that each \( \lambda_j := \ell \tilde{a}_j \) is a weight; which then lies in \( P_{\ell} \). We furthermore choose \( \ell \) so that \( \sum_{j=1}^{s} \lambda_j \) is in the root lattice and consider the space of conformal blocks \( V(G, g, s, \Delta, \ell) \) associated to this collection \( \Delta = \{ \lambda_1, \lambda_2, \ldots, \lambda_s \} \). We can dilate simultaneously the weights \( \lambda_j \) and the level \( \ell \) by a factor \( k \). Then, the function

\[
k \mapsto \dim(V(G, g, s, [k\lambda_1, k\lambda_2, \ldots, k\lambda_s], k\ell))
\]

is a quasi-polynomial in \( k \) of degree \( m = \dim(G)(g - 1) + s|R^+| \), the complex dimension of the moduli space \( \mathcal{M}(G, g, s, \mathbb{C}) \). The volume computes the highest
term of this quasi-polynomial. More precisely,
\[
\text{vol}(\mathcal{M}(G, g, s, C)) = \lim_{k \to \infty} (\ell k)^{-m} \dim(V(G, g, s, [k\ell\tilde{a}_1, \ldots, k\ell\tilde{a}_s], k\ell)).
\]

**Proposition 3.1.** Let \( \mathfrak{a} = \{a_1, \ldots, a_s\} \) be a collection of regular rational elements in \( \mathfrak{A} \). Let \( \text{vol}(G, g)(\mathfrak{a}) \) denote the symplectic volume of the moduli space \( \mathcal{M}(G, g, s, C) \). Then,
\[
\text{vol}(G, g)(\mathfrak{a}) = \left(\frac{\ell g}{|W|}\right)^{p(2g-2+s)} (-1)^{(g-1)} |\Phi(G)| W(\Phi(G), P, g, s)(\mathfrak{a}),
\]
where \( p \) is the number of short positive roots of \( G \), and \( \epsilon_G = 2 \) for any simple Lie group except for \( G_2 \), where \( \epsilon_G = 3 \).

We recall that for simply laced groups \( p = 0 \) since all roots are considered as long.

**Proof.** Choose \( \ell \) so that each \( \lambda_j := \ell \tilde{a}_j \) lies in \( P_\ell \) and \( \sum_{j=1}^s \lambda_j \) is a root. Then,
\[
\text{vol}(G, g)(\mathfrak{a}) = \lim_{k \to \infty} \frac{1}{(\ell k)^m} V(G, k\Lambda, g, k\ell),
\]
where \( m = \dim(G)(g-1) + s|R^+| \) is the dimension of \( \mathcal{M}(G, g, s, C) \) and
\[
V(G, k\Lambda, g, k\ell) = \left(\frac{\ell g}{|W|}\right)^{p(2g-2+s)} (-1)^{(g-1)}\sum_{t \in T^{reg}_\ell/W} \frac{\chi_V(k\Lambda)(t)}{\Delta(t)^{g-1}}.
\]
An element \( \mu \in P_\ell \) determines a unique regular element \( h_\mu \in \mathfrak{A} \), the image of \( \frac{\mu + R^+}{k\ell + R^+} \) under the identification given by the basic invariant form. Denote the image of \( h_\mu \) under the exponential map by \( t_\mu \in T_\mathbb{C}^\ast \). The set \( \{t_\mu : \mu \in P_\ell\} \) form a set of representatives for \( T^{reg}_\ell/W \). Using also the bijection between sets \( P_\ell \) and \( P_{\ell + h} \) given by \( \mu \mapsto \mu + \rho \),
\[
V(G, k\Lambda, g, k\ell) = \left(\frac{\ell g}{|W|}\right)^{p(2g-2+s)} \sum_{\mu + \rho \in P_{\ell + h}} \frac{\chi_V(k\Lambda)(t_\mu)}{\Delta(t_\mu)^{g-1}}
\]
\[
= \left(\frac{\ell g}{|W|}\right)^{p(2g-2+s)} \sum_{\mu + \rho \in W_{\ell + h}} \frac{\prod_{j=1}^s J(e^{k\lambda_j + \rho})(t_\mu)}{(J(e^\rho)(t_\mu))^\Delta(t_\mu)^{g-1}}
\]
\[
= \left(\frac{\ell g}{|W|}\right)^{p(2g-2+s)} \sum_{\mu + \rho \in W_{\ell + h}} \frac{\prod_{j=1}^s J(e^{k\lambda_j + \rho})(t_\mu)}{(J(e^\rho)(t_\mu))^2 g^{-2+s}}.
\]
The second line above follows from the fact that both \( \chi_V(k\lambda)(t) \) and \( \Delta(t) \) are \( W \)-invariant. The third line follows from the second by the identity
\[
\Delta(t) = J(e^\rho)(t) J(e^\rho)(t) = (-1)^{R^+} (J(e^\rho)(t))^2. \quad (3.1.1)
\]
We now analyze \( V(G, k\Lambda, g, k\ell) \) as \( k \) gets large.
The expression $\prod_{j=1}^{s} J(e^{k\lambda_j + \rho})(t_{\mu})$ in the summand is equal to
\[
\prod_{j=1}^{s} \sum_{w \in W} \varepsilon(w) e^{w(k\lambda_j + \rho)}(t_{\mu}) = \prod_{j=1}^{s} \sum_{w \in W} \varepsilon(w) \exp \left( 2i\pi \left( \mu + \rho \frac{w(k\lambda_j + \rho)}{k\ell + h} \right) \right).
\]

Now as $k$ gets large, the expression $\exp \left( 2i\pi \left( \mu + \rho \frac{w(k\lambda_j + \rho)}{k\ell + h} \right) \right)$ approaches $exp(2i\pi(\mu + \rho|w\lambda_j))$. Observe also that the set $W \cdot P'_{k\ell + h}$ approaches $P_{\text{reg}}$. Denote an element $\mu + \rho$ of this limiting set by $\gamma$. Hence, $\prod_{j=1}^{s} J(e^{k\lambda_j + \rho})(t_{\mu})$ approaches $\prod_{j=1}^{s} \sum_{w \in W} \varepsilon(w) e^{2i\pi \gamma w(a_j)} = N_{\alpha}(2i\pi \gamma)$.

Now we analyze the denominator of the summand,
\[
\frac{1}{J(e^\rho)(t_{\mu})} = \prod_{\alpha > 0}(e^{\alpha/2}(t_{\mu}) - e^{-\alpha/2}(t_{\mu})) = \frac{1}{\prod_{\alpha > 0} 2i\sin(\pi(\alpha|\mu + \rho)_{k\ell + h})}.
\]
This expression explodes at each central vertex and the contribution from each, as $k$ gets large, is $\prod_{\alpha > 0} \frac{1}{2i\sin(\pi(\alpha|\mu + \rho)_{k\ell + h})}$. Also observe that, for $z \in Z(G)$ both $T'_{\ell}^{\text{reg}}$ and $\Delta(t)$ is invariant under $t \mapsto tz$. Moreover, since $\sum_{j=1}^{s} \lambda_j$ is in the root lattice by construction, $\chi_{V(k\lambda_j)}(t)$ is also invariant. Therefore, we may add all these equal contributions from central vertices. (see also Remark 5.8. [14]). Hence, we get that the expression
\[
\sum_{\mu + \rho \in W \cdot P'_{k\ell + h}} \prod_{j=1}^{s} \frac{J(e^{k\lambda_j + \rho})(t_{\mu})}{J(e^\rho)(t_{\mu})}^{2g-2+s}
\]
approaches
\[
|Z(G)|(k\ell + h)^{R^+|(2g-2+s)} \sum_{\gamma \in P_{\text{reg}}} N_{\alpha}(2i\pi \gamma) \prod_{\alpha > 0}(2i\pi(\alpha|\gamma))^{2g-2+s}.
\]

By virtue of the normalization in the basic invariant form, if $\alpha$ is a long root we have $\langle H_{\alpha}, \gamma \rangle = (\alpha|\gamma)$; otherwise $\langle H_{\alpha}, \gamma \rangle = 0$. Using also that the dimension of $G$ is $r + 2|R^+|$, and that $|R^+| = |\Phi(G)|$, we obtain
\[
\lim_{k \to \infty} \frac{1}{(k\ell)^m} V(G, k\lambda, g, k\ell) = (fq)^{g-1} |Z(G)|^{[\Phi(G)](g-1)} e^{(2g-2+s)} W(\Phi(G), P, g, s)(\alpha)
\]
as claimed.

\begin{remark}
In the case of one marking, the Verlinde formula reduces to
\[
V(G, \lambda, g, \ell) = (fq)^{g-1}(\ell + h)^{t(g-1)} \sum_{t \in T_{\ell}^{\text{reg}}} \frac{e^{\lambda(t)}}{D(t)\Delta(t)^{g-1}}.
\]
\end{remark}
where $D(t) = \prod_{\alpha > 0}(1 - e^{-\alpha(t)})$.

Following the same line of arguments as in the proof of Proposition 3.1 we get that for $s = 1$ with $\lambda = \ell \alpha$ lying in the root lattice,

\[
\text{vol}(G, g)(a) = (fq)^{g-1} |Z| \epsilon_{G}^{(2g-1)}(-1)^{(g-1)} \Phi \sum_{\gamma \in P^+} \prod_{H, \alpha \in \Phi} (2\pi \langle H, \gamma \rangle)^{2g-1}.
\]

That is,

\[
\text{vol}(G, g)(a) = (fq)^{g-1} |Z| \epsilon_{G}^{(2g-1)}(-1)^{(g-1)} \Phi \mathcal{B}(\Phi_{2g-1}, \bar{Q})(a).
\]

3.1. Volume of the moduli space as a function of the volume of $T$ and $G$

Let us recall the formula for the symplectic volume of the moduli space $\mathcal{M}(G, g, s, C)$ for a set of $s$ regular conjugacy classes $C = (C_{j})$ in $G$ as given by E. Witten ([16] equation 4.1.14),

\[
\text{vol}(\mathcal{M}(G, g, s, C)) = \frac{|Z(G)| (2\pi)^{2m}}{\text{vol}(G)^{2g-2} \text{vol}(G/T)^{*}} \sum_{\lambda \in P^+} \frac{\prod_{j=1}^{s} [\chi_{\lambda}(C_{j}) \sqrt{\Delta(C_{j})}]}{\dim V_{\lambda} 2g-2+s}
\]

where $2m$ is the real dimension of $\mathcal{M}(G, g, s, C)$, and $P^+ = P \cap h^*_{\mathbb{R}}$ is the set of dominant weights parametrizing irreducible representations of $G$. Above $\text{vol}(G)$, $\text{vol}(G/T)$ are Riemannian volumes of $G$ and $G/T$ which we now express following Bourbaki (Ch. IX, pages 396-411):

Choose a $g$-invariant scalar product on $g$. This determines a Lebesgue measure $\mu$ on $g$, via identification of $g$ with $\mathbb{R}^n$ by an orthonormal basis. Similarly let $\tau$ be the Lesbegue measure on $t$ corresponding to the restriction of the scalar product on $t$. We can construct from $\mu$ and $\tau$ Haar measures $\mu_G$ and $\mu_T$ on $G$ and $T$ respectively.

Since we aim to compare the volume formula in Proposition 3.1 with that of Witten in Equation (3.2.2), we choose the normalized Killing form as the $g$-invariant scalar product in the above construction, as this was our choice in the previous section. Then, for this choice, with respect to $\mu_G$ and $\mu_T$ constructed as above, we get that

\[
\text{vol}(G) = (fq)^{1/2} (2\pi)^{|R^+|+r} \frac{1}{\prod_{\alpha > 0}(\alpha|\rho)} \text{vol}(G/T) = (2\pi)^{|R^+|} \frac{1}{\prod_{\alpha > 0}(\alpha|\rho)}.
\]

Observe that from formula (3.1.1), $\Delta(t)$ takes positive values on a regular element $t$. Then, for $C_{j}$ the adjoint orbit of $\exp(a_{j})$, we may write

\[
\chi_{\lambda}(C_{j}) = \sum_{w \in W} \varepsilon(w) e^{2\pi i \langle w(\lambda + \rho), a_{j} \rangle} \sqrt{\Delta(C_{j})}.
\]

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Let \( d(\gamma) = \prod_{\alpha > 0} \langle \gamma, H_\alpha \rangle \langle \rho, H_\alpha \rangle \), it computes the dimension of the irreducible representation \( V_{\gamma - \rho} \). Then we have

\[
\sum_{\lambda \in P^+} \frac{\prod_{j=1}^r \chi_{V_\lambda}(C_j) \sqrt{\Delta(C_j)}}{\dim V_\lambda^{2g-2+s}} = \sum_{\lambda \in P^+} \prod_{j=1}^s N_{a_j} (2i\pi (\lambda + \rho)) \frac{1}{i^{s|R^+|d(\lambda + \rho)^{2g-2+s}}.
\]

Observe that the summand above is invariant under the Weyl group (both the numerator and the denominator are anti-invariant by factor \((\text{sign}(w))^s\) for a Weyl group element \(w\)). Using this invariance, we get

\[
\sum_{\lambda \in P^+} \frac{\prod_{j=1}^r \chi_{V_\lambda}(C_j) \sqrt{\Delta(C_j)}}{\dim V_\lambda^{2g-2+s}} = \frac{1}{|W|} \sum_{\gamma \in \tilde{P}^{\text{reg}}} \prod_{j=1}^s N_{a_j} (2i\pi \gamma)
\]

Inserting the expressions for the volume of \( G \) and \( G/T \) into Equation (3.2.2), all \((2\pi)\) factors cancel, and combining the terms we get

\[
\text{vol}(M(G, g, s, \mathcal{C})) = \frac{|Z|}{|W|} (fg)^{g-1} \frac{(\prod_{\alpha > 0} \langle \rho, H_\alpha \rangle)^{2g-2+s}}{(\prod_{\alpha > 0} \langle \alpha | \rho \rangle)^{2g-2+s}} (-1)^{(g-1)|R^+|} |W(\Phi(G), P, g)(a)|
\]

which is precisely the formula that we obtained in Proposition 3.1.

4. Various examples of volume calculations

Example 4.1. We now compute the volume of the moduli space of SU(3) bundles on a Riemann surface of genus one.

Simple roots are \( \alpha_1 = e_1 - e_2 \), \( \alpha_2 = e_2 - e_3 \), and fundamental weights are \( \omega_1 = \frac{e_1 - e_2 - e_3}{3} \), \( \omega_2 = \frac{e_1 + e_2 - 2e_3}{3} \). The positive coroots are

\[
\Phi(\text{SU}(3)) = \{ H_{\alpha_1} = e^1 - e^2, H_{\alpha_2} = e^2 - e^3, H_{\alpha_1 + \alpha_2} = e^1 - e^3 \}
\]

and \( P = \mathbb{Z}\omega_1 + \mathbb{Z}\omega_2 \). Let \( \gamma = n_1\omega_1 + n_2\omega_2 \). Then \( \gamma \in \tilde{P}^{\text{reg}} \) if and only if \( n_1 \neq 0, n_2 \neq 0 \) and \( n_1 + n_2 \neq 0 \). Now consider \( a = a_1H_{\alpha_1} + a_2H_{\alpha_2} = a_1(e^1 - e^3) + (a_2 - a_1)(e^2 - e^3) \in h_\mathfrak{g} \). Suppose that \( a \) is a regular element in \( \mathfrak{h} \), in other words, \( 2a_1 - a_2 > 0 \), \( 2a_2 - a_1 > 0 \) (in particular \( a_1 > 0 \) and \( a_2 > 0 \)) and \( \theta(a_1H_{\alpha_1} + a_2H_{\alpha_2}) = a_1 + a_2 < 1 \).

We compute the volume using Formula (3.2.1). We have \( s = 1, p = 0, q = 1, f = 3 \) and \( |Z(\text{SU}(3))| = 3 \); hence, for \( g = 1 \), \( 2g^{(2g-1)}(fg)^{g-1}|Z(G)| = 3 \). Then,

\[
\text{vol}(\text{SU}(3), 1)(a) = 3 \sum_{n_1 \neq 0, n_2 \neq 0} \frac{q^{2i\pi (n_1a_1 + n_2a_2)}}{(2i\pi n_1)(2i\pi n_2)(2i\pi (n_1 + n_2))}
\]

\[
= \begin{cases} 
-1/2(1 + a_1 - 2a_2)(a_1 - 1 + a_2)(2a_1 - a_2) & a_1 \leq a_2 \\
-1/2(1 + a_1 - 2a_2)(a_1 - 1 + a_2)(2a_1 - 1 - a_2) & a_1 \geq a_2 
\end{cases}
\]

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Example 4.2. With the notation of Example 4.1, we make similar computations for SU(3) when genus \( g = 2 \).

In this case, \( s = 1, p = 0, q = 1, f = 3, |Z(SU(3))| = 3 \), hence, for \( g = 2, 2^{(2g-1)}(f_q)^{g-1}|Z(G)|(-1)^{(g-1)|\Phi|} = -3^2 \). Then,

\[
\text{vol}(SU(3), 2)(a) = -9 \sum_{n_1 \neq 0, n_2 \neq 0, n_1 + n_2 \neq 0} e^{2 i \pi (n_1 a_1 \theta_1 + n_2 a_2)} \frac{(2i \pi n_1)^3 (2i \pi n_2)^3 (2i \pi (n_1 + n_2))^3}{(2i \pi n_1)^3 (2i \pi n_2)^3 (2i \pi (n_1 + n_2))^3}
\]

\[
= \begin{cases} 
1/40320(a_2 - 2a_1)(a_2 - 1 + a_1)(-1 + 2a_2 - a_1)P_1 & a_1 \leq a_2 \\
1/40320(a_2 + 1 - 2a_1)(2a_2 - a_1)(a_2 + 1 + a_1)P_2 & a_1 \geq a_2
\end{cases}
\]

where the polynomials \( P_1 \) and \( P_2 \) above are too long to be included in here.

Example 4.3. We now compute the volume of the moduli space of Spin(5) bundles on a Riemann surface of genus \( g = 1 \) with one marking.

Positive roots are \( \{a_1 + a_2 = e_1, a_2 = e_2, \theta = e_1 + e_2, a_1 = e_1 - e_2\} \), with associated coroots \( H_{e_1} = 2e_1^1, H_{e_2} = 2e_2^2, H_{e_1 - e_2} = e_1^1 - e_2^2, H_{e_1 + e_2} = e_1^1 + e_2^2 \).

Let \( a = a_1 H_{a_1} + a_2 H_{a_2} \) be a regular element in \( \mathfrak{a} \); in other words, \( a_1 > a_2, 2a_2 > a_1, 2a_2 < 1 \). We can express \( a \) as \( a = t_1 e_1^1 + t_2 e_2^2 \) (with \( t_1 = a_1 \) and \( t_2 = 2a_2 - a_1 \), \( t_1 \) and \( t_2 \) satisfy \( t_1 > t_2, t_2 > 0, t_1 + t_2 < 1 \). We calculate the volume for \( B_2 \) and genus \( g = 1 \) employing the Formula (3.2.1). In this case, \( s = 1, p = 2, q = 2, f = 2, |Z(Spin(5))| = 2 \). Hence, for \( g = 1, 2^{(2g-1)}(f_q)^{g-1}|Z(Spin(5))|(-1)^{(g-1)|\Phi|} = 8 \). We get,

\[
\text{vol}(B_2, g = 1)(a) = \frac{1}{2}(t_2(t_1 - 1)(t_1 - 1 + t_2)(t_1 - 2)) = \frac{1}{2}(a_2 - a_1)(a_1 - a_2)(-1 + 2a_2)(a_1 - a_2).
\]

Example 4.4. With the notation of Example 4.3, we compute the volume of the moduli space of Spin(5) bundles on a Riemann surface of genus one and two markings.

Let \( a = \{a_1, a_2\} \), where \( a_1 \) and \( a_2 \) are regular elements in \( \mathfrak{a} \). Write \( a_1 = t_1 e_1^1 + t_2 e_2^2 \) and \( a_2 = u_1 e_1^1 + u_2 e_2^2 \). Then the function \( \text{vol}(B_2, 1)(a) \) is a piecewise polynomial function of \( t_1, t_2, u_1, u_2 \). For example, choose \( v_1 = \frac{1}{2} e_1^1 + \frac{1}{2} e_2^2 \), \( v_2 = \frac{1}{2} e_1^1 + \frac{1}{2} e_2^2 \) and consider \( \tau(v) \subset \mathfrak{a} \times \mathfrak{a} \), the open set determined by the condition that \( a_1 + w(a_2) \) is in the same cone as \( v_1 + w(v_2) \) for each element \( w \) in the Weyl group of \( B_2 \). Then for \( a \in \tau(v) \), we have

\[
\text{vol}(B_2, 1)(a) = 4W(\Phi(B_2), P, 1, 2)(a)
\]

\[
= -\frac{1}{60} u_2 u_1^5 - \frac{1}{12} u_2 u_2 u_1 u_3^3 - \frac{1}{6} u_2 u_1 u_1^3 - \frac{1}{6} u_2 u_2 u_1 u_2^2 - \frac{1}{6} u_2 u_2 u_2 u_2^3 u_1^3 - \frac{1}{12} u_2 u_2^3 u_1 u_2^3 + \frac{1}{12} u_2 u_3 u_1^3 - \frac{1}{6} u_2 u_2 u_1 u_1^3 - \frac{1}{4} u_2 u_2 u_1 u_2^3 u_1^3 - \frac{1}{4} u_2 u_2^3 u_1 u_1^3 + \frac{1}{6} u_2^3 u_2 u_1 u_1^3 - \frac{1}{6} u_2^3 u_2 u_1 u_1^3 - \frac{1}{6} u_2^3 u_2 u_1 u_1^3 - \frac{1}{6} u_2^3 u_2 u_1 u_1^3 - \frac{1}{6} u_2^3 u_2 u_1 u_1^3
\]

5. More examples

In this section we compute some instances of volumes of moduli spaces of flat \( G \)-connections for classical simple Lie groups \( G \) using the formula given in Proposition 3.1. We remark that in this case \( \epsilon_G \) is always 2.
We will denote by $c_{\text{vol}}$ the factor

$$c_{\text{vol}} := 2^p(2g-2+s)(f q)^{g-1}|Z(G)|(-1)^{(g-1)|\Phi(G)|}|W|^{-1}.$$ 

For convenience, we list values of the parameters in $c_{\text{vol}}$ for each type of classical simple Lie group in Table 1.

5.1. Tables of volumes of moduli spaces

In the case of no marking ($s = 0$) we denote the volume simply by $\text{vol}(G, g)$. We list some values of $\text{vol}(G, g)$ for classical simple Lie groups in Tables 2 and 3. We also list some values of the factor $c_{\text{vol}}$ that we need in Section 5.2 to compare our computations with other numerical results in literature.

Computations are very quick for rank less or equal to 4 (and relatively small genus). Beyond rank 5, computations cannot be made within a time limit of half-hour with our method.

Here are some explicit running times regarding the volume tables:
Type A, rank 4 and genus 4 running time less then 1 sec.
Type A, rank 5 and genus 2 running time less then 1 sec.
Type B, rank 4 and genus 3 running time less then 1 sec.
Type B, rank 5 and genus 3 running time 5 hours.
Type C and rank 4 and genus 4 running time less then 1 sec.
Type C, rank 5 and genus 2 less then 1 sec.
Type D, rank 5 and genus 2 running time 2 sec.
Type D, rank 4 and genus 4 running time half an hour.

All experiments were done with Maple 15 on a MacPro with a Quad-Core Intel Xeon machine running at 2.93GHz.
| G | g | $\text{vol}(G, g)$ | $c_{\text{vol}}$ |
|---|---|-----------------|--------------|
| 2 | 1 | 1 1/2 | 1/2 |
| 3 | 1/2 | 111 13/16 | 1/2 |
| 4 | 1 | 1111 3/16 | 1/2 |
| 5 | 1/2 | 11111 1/16 | 1/2 |
| 6 | 1/2 | 111111 1/16 | 1/2 |
| 7 | 1/2 | 1111111 1/16 | 1/2 |
| 8 | 1/2 | 11111111 1/16 | 1/2 |
| 9 | 1/2 | 111111111 1/16 | 1/2 |
| 10 | 1/2 | 1111111111 1/16 | 1/2 |

| A₂ | 2 | 1/2 | 1/2 |
| 3 | 1/2 | 1/2 |
| 4 | 1/2 | 1/2 |
| 5 | 1/2 | 1/2 |
| 6 | 1/2 | 1/2 |
| 7 | 1/2 | 1/2 |
| 8 | 1/2 | 1/2 |
| 9 | 1/2 | 1/2 |
| 10 | 1/2 | 1/2 |

| A₃ | 2 | 1/2 | 1/2 |
| 3 | 1/2 | 1/2 |
| 4 | 1/2 | 1/2 |
| 5 | 1/2 | 1/2 |
| 6 | 1/2 | 1/2 |
| 7 | 1/2 | 1/2 |
| 8 | 1/2 | 1/2 |
| 9 | 1/2 | 1/2 |
| 10 | 1/2 | 1/2 |

| A₄ | 2 | 1/2 | 1/2 |
| 3 | 1/2 | 1/2 |
| 4 | 1/2 | 1/2 |
| 5 | 1/2 | 1/2 |
| 6 | 1/2 | 1/2 |
| 7 | 1/2 | 1/2 |
| 8 | 1/2 | 1/2 |
| 9 | 1/2 | 1/2 |
| 10 | 1/2 | 1/2 |

| A₅ | 2 | 1/2 | 1/2 |
| 3 | 1/2 | 1/2 |
| 4 | 1/2 | 1/2 |
| 5 | 1/2 | 1/2 |
| 6 | 1/2 | 1/2 |
| 7 | 1/2 | 1/2 |
| 8 | 1/2 | 1/2 |
| 9 | 1/2 | 1/2 |
| 10 | 1/2 | 1/2 |

Table 2: Witten volumes with $s = 0$ type $A$, $D$
Table 3: Witten volumes with $s = 0$ type $B, C$
5.2. Comparison results

In this section we compare some of our computations of \( \text{vol}(G, g) \) with that of Komori-Matsumoto-Tsumura ([6],[7],[8],[9]). The setting is as follows.

Consider a simple, connected, compact Lie group \( G \) of rank \( r \). Here we do not assume that \( G \) is simply-connected. Let \( L \) be the weight lattice of \( G \). Let \( P \) be the weight lattice of the simply connected group covering \( G \) and let \( Q \) be its root lattice. Then, \( Q \subset L \subset P \). We denote, as before, by \( P^+ \) the monoid of dominant weights. Let \( L^+ = L \cap P^+ \).

Let \( s = [s_0] \) be a sequence of real variables indexed by positive roots \( R^+ \). For \( v \in \mathfrak{h}_R \), Komori-Matsumoto-Tsumura introduced

\[
\zeta(s, v, G) = \sum_{\gamma \in \rho + L^+} e^{2\pi i (v, \gamma)} \prod_{\alpha \in R^+} \frac{1}{(\gamma(\alpha))^s_\alpha}.
\]

If \( G \) is simply connected, then \( L = P \), and we may denote \( \zeta(s, v, G) \) by \( \zeta(s, v, g) \), or for the Lie algebra \( g \) of type \( X_r \) by \( \zeta(s, v, X_r) \) as in [8].

Example 5.1. Consider the simply connected group \( G = SU(4) \); its positive roots are \( [e_1 - e_2, e_2 - e_3, e_3 - e_4, e_1 - e_3, e_2 - e_4, e_1 - e_4] \).

The monoid of dominant weights is freely generated by fundamental weights \( \omega_1, \omega_2 \) and \( \omega_3 \) that are dual to simple coroots \( e^1 - e^1, e^2 - e^4 \) and \( e^3 - e^3 \) respectively. Then, if we order the exponents \( s = [s_1] \) with respect to the order of the roots as given above,

\[
\zeta(s, v, SU(4)) = \zeta(s, v, A_3)
\]

\[
= \sum_{m_1=1}^{\infty} \sum_{m_2=1}^{\infty} \sum_{m_3=1}^{\infty} \frac{e^{2\pi i (m_1 \omega_1 + m_2 \omega_2 + m_3 \omega_3)}}{(m_1 + m_2 + m_3)^{s_1}}.
\]

The series \( \zeta(s, v, G) \) converges when the exponents \( s_0 \) are sufficiently large. Let \( S = \sum s_n \). Suppose \( s_0 \) are the same for all short roots, respectively for all long roots, and both are equal to positive even integers (that are not necessarily the same positive even integers). Then \( (2\pi)^{-S} \zeta(s, 0, G) \) is rational. Indeed, using the invariance of the sum under the Weyl group \( W \), \( (2\pi)^{-S} \zeta(s, 0, G) \) is proportional to a Bernoulli series (with repetition of coroots in \( \Phi \) matching the exponent data) which is obtained by summing over all the regular elements of the full lattice \( L \). More precisely,

\[
\frac{\zeta(s, 0, G)}{(2\pi)^S} = |W|^{-1} S \sum_{\gamma \in L_{\text{reg}}} \frac{1}{(2\pi i (\gamma, H_0))^s_\gamma},
\]

where the series on the right hand side is a multiple Bernoulli series which has (in the case that it converges absolutely) rational value.

If all \( s_0 \) are equal to an even integer \( 2k \), we denote the sequence \( s = [s_0] \) by \( s_{2k} \). Then, for exponents \( s_{2k} \), and \( G \) simply connected, we may compute \( \zeta(s_{2k}, 0, G) \) using the Witten volume formula for \( g = k + 1 \),

\[
\zeta(s_{2k}, 0, G) = |W|^{-1} (2\pi)^{2k|R^+|} (-1)^k |R^+| W(\Phi(G), L, k + 1)(0)
\]

\[
= |W|^{-1} (2\pi)^{2k|R^+|} (-1)^k |R^+| \frac{1}{c_{\text{vol}}} \text{vol}(G, k + 1)(0). \tag{5.1.2}
\]
Thus we can use the values of the volume listed in the tables of the previous section to compute some instances of the series \( \zeta(s_{2k}, 0, G) \). We now demonstrate some computations of \( \zeta(s_{2k}, 0, G) \).

5.2.1. Examples of type \( A_r \)

Let \( n = r + 1 \). We consider the simply connected group \( G = SU(n) \). If we write \( N = |R^+| = \frac{n(n-1)}{2} \), then

\[
\zeta(s_{2k}, 0, A_r) = (-1)^N (2\pi)^{2kN} \frac{1}{n!} \frac{1}{c_{\text{vol}}} \text{vol}(SU(n), k + 1)(0),
\]

where \( c_{\text{vol}} = n^{k+1} (-1)^k \frac{n(n-1)}{n!} \). Thus we obtain the values of \( \zeta(s_{2k}, 0, A_r) \) for \( n = 3, 4, 5, 6 \) using Table 2.

For instance, if \( n = 3 \) (that is \( r = 2 \)), and \( k = 1 \), then we have \( N = 3 \), \( \text{vol}(SU(3), 2)(0) = \frac{1}{20160} \) and \( c_{\text{vol}} = \frac{-3}{2} \), and we obtain

\[
\zeta(s_{2}, 0, A_2) = (2\pi)^6 (-1)^3 \frac{1}{3! 9} \frac{1}{13936140662513412310095846} = \frac{\pi^6}{2835}
\]
as in [9] equation (7.11).

We give one other example whose parameters are not contained in the tables. Consider \( n = 4, k = 5 \). Then, \( N = 6 \) and

\[
\zeta(s_{2k}, 0, A_3) = (2\pi)^{60} \times \frac{1}{13936140662513412310095846} = 58203152419058513584890890509712229288124323632762771449711578369140625
\]

5.2.2. Examples of type \( B_r, C_r \) and \( D_r \)

For root systems of type \( B_r, C_r \) and \( D_r \), the number of positive roots is \( N = r^2 \). For example, for \( B_r \) when all \( s_n = 2k \),

\[
\zeta(s_{2k}, 0, B_r) = \frac{1}{r! 2^k} (2\pi)^{2kN} (-1)^N B(H^{BC}_r, Q^{B}_{s_{2k}})(0).
\]

Explicitly for \( C_2 \), positive roots are \([e_1 - e_2, 2e_2, 2e_1, e_1 + e_2]\). We order the exponents with respect to the order given in the list of positive roots. Then,

\[
\zeta([s_1, s_2, s_3, s_4], 0, C_2) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{1}{m^{s_1} n^{s_2} (m+n)^{s_3} (m+2n)^{s_4}}.
\]

In the particular case of \( s_2 = [2, 2, 2, 2] \), using Table 3,

\[
\zeta(s_{2}, 0, C_2) = \frac{1}{8} (-1)^4 (2\pi)^8 \frac{1}{16 604800} = \frac{1}{302400} \pi^8,
\]

which is the equation (7.23) of [9].
We also give an example of $D_4$ with all exponents equal to 6 (that is $k = 3$ and $s_6 = [6, 6, 6, 6, 6, 6, 6, 6, 6, 6, 6]$).

$$\zeta(s_6, 0, D_4) = \pi^{72} \times$$

$$\frac{537255094453148798111597103943896132463}{2177052415822325076785681065345104311303415213321829119940284380871681463708800000000000000000}$$

It is also possible to compute $\zeta(s, 0, G)$ when the exponents in the list $s = [s_1, s_2, s_3, s_4]$ are distinct positive even integers for short and long roots. We conclude with one example of this kind.

Consider the list of exponents $[2, 4, 4, 2]$ corresponding to the list of positive roots $[e_1 - e_2, 2e_2, 2e_1, e_1 + e_2]$ of $C_2$. Then,

$$\zeta([2, 4, 4, 2], 0, C_2) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{1}{m^{2n}(m+n)^4(m+2n)^2} = \pi^{12} \frac{53}{6810804000},$$

which coincides with equation (4.30) of [9].

5.3. Some multiple zeta values

Let $k$ be a positive integer. Consider the multiple zeta series

$$\zeta_r(2k, 2k, \ldots, 2k) := \sum_{m_1=1}^{\infty} \sum_{m_2=1}^{\infty} \cdots \sum_{m_r=1}^{\infty} \frac{1}{m_1^{2k}(m_1 + m_2)^{2k}} \cdots \frac{1}{(m_1 + m_2 + \cdots + m_r)^{2k}}.$$

Following [6], we want to demonstrate how the above series can be computed using the Bernoulli series $B(H_r^{BC}, \hat{Q}_C, g_\kappa^C)(0)$ for the root system of type $C_r$, where the exponents $s = [s_\alpha]$ are taken to be 0 for long positive roots, and $2k$ for short positive roots. Using the invariance of the sum under the Weyl group, which is of order $2^r r!$ for $C_r$,

$$B(H_r^{BC}, \hat{Q}_C, g_\kappa^C)(0) = 2^r r! \sum_{\gamma \in (P_C^\vee)_{reg}} \frac{1}{\prod_{\alpha > 0} (2\pi (H_\alpha, \gamma))^{\omega_\alpha}}.$$

A dominant integral regular weight $\gamma \in (P_C^\vee)_{reg}$ is of the form $\gamma = \sum_{i=1}^{r} m_i \omega_i$ with $m_i \geq 1$ (where $\omega_i$ denote fundamental weights). Recall that the root system of type $C_r$ admits $r$ long roots $\{2e_i\}_{1 \leq i \leq r}$, with corresponding (short) coroots $\{H_{2e_i} = e_i\}_{1 \leq i \leq r}$. If we express $H_{2e_i} = e_i = (e^i - e^{i+1}) + (e^{i+1} - e^{i+2}) + \cdots + e_r$, then $\langle H_{2e_i}, \gamma \rangle = m_i + m_{i+1} + \cdots + m_r$. Thus,

$$\zeta_r(2k, 2k, \ldots, 2k) = (-1)^k (2\pi)^{2kr} \frac{1}{2^r r!} B(H_r^{BC}, \hat{Q}_C, g_\kappa^C)(0).$$

For example, $\zeta_2(4, 4) = \frac{\pi^8}{113400}$, $\zeta_3(4, 4, 4, 4) = \frac{\pi^{20}}{548828480360160000}$ and $\zeta_3(6, 6, 6, 6) = \frac{\pi^{30}}{1347828286825972065254765625}$. 

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6. Appendix: Szenes formula

Let \( \mathcal{H} \) be an arrangement of hyperplanes compatible with a lattice \( \Lambda \). Let \( g \in \mathcal{R}_\mathcal{H} \). Consider

\[
B(\mathcal{H}, \Lambda; g)(v) = \sum_{\gamma \in \Gamma_{\text{reg}}(\mathcal{H})} g(2i\pi \gamma) e^{2i\pi \langle v, \gamma \rangle}.
\]

This function (a generalized function on \( V \)) coincide with a polynomial function \( B(\mathcal{H}, \Lambda; g) \) on a tope \( \tau \) (see Proposition 1.25). The piecewise polynomial function \( P(\mathcal{H}, \Lambda; g) \) has been defined in Definition 1.14. Following Szenes [12], we prove the following formula.

**Theorem 6.1.** (Szenes) Let \( g \in \mathcal{R}_\mathcal{H} \). On \( V_{\text{reg}}(\mathcal{H}, \Lambda) \) we have the equality

\[
B(\mathcal{H}, \Lambda; g) = P(\mathcal{H}, \Lambda; g).
\]

We recall that, for \( f \in S_\mathcal{H} \), \( Z^\Lambda(v)(f)(z) = \sum_{\gamma \in \Gamma} f(2i\pi \gamma - z) e^{(v, 2i\pi \gamma - z)} \), and \( P(\mathcal{H}, \Lambda; g)(v) \) is the trace on \( S_\mathcal{H} \) of the operator \( A(v, g) : S_\mathcal{H} \to S_\mathcal{H} \) defined by

\[
f(z) \mapsto R( e^{(z,v)g(z)}(Z^\Lambda(v)f)(z)).
\]

(6.1.1)

Here \( R : \mathcal{R}_\mathcal{H} \to S_\mathcal{H} \) is the total residue.

We first consider the one dimensional case where \( V = \mathbb{R} \), and \( \Lambda = \mathbb{Z} \). Here \( \mathcal{H} = \{0\} \), with equation \( z = 0 \). The topes are the intervals \( [n, n+1] \), and the space \( S_\mathcal{H} \) is one dimensional with basis \( f_\sigma = \frac{1}{z} \).

Let \( \sigma = [0, 1] \). Assume \( v \in \sigma \) so that \( \langle v \rangle = 0 \). If we consider \( g(z) = \frac{1}{z} \), the formula to be proven is

\[
\sum_{n \neq 0} e^{2i\pi n v} = \text{Res}_{z=0}(\frac{1}{z} e^{\frac{2i\pi v}{z}}(Z^\Lambda(\sigma)f_\sigma)(z)).
\]

(6.1.2)

As \( Z^\Lambda(\sigma)(f_\sigma)(z) = \frac{1}{1-e^z} \) (see Example 1.10), we have to verify that

\[
\sum_{n \neq 0} e^{2i\pi n v} = \text{Res}_{z=0}(\frac{1}{z} e^{\frac{2i\pi v}{z}} \frac{1}{1-e^z}).
\]

The poles of the function \( \frac{1}{1-e^z} \) consist of the elements \( 2i\pi n \), with \( n \in \mathbb{Z} \). When \( k \geq 0 \), the equality above follows from the residue theorem in one variable. If \( k < 0 \), both sides vanish (the left hand side gives a generalized function supported on \( \mathbb{Z} \), the right hand side has no poles).

Szenes formula generalizes this result in higher dimensions, which we aim to demonstrate below.

**Proof.** Our proof is a slightly modified version of Szenes’s proof where we use the total residue as opposed to iterated residue.

We first remark that using the comparison formula (1.14.1) and those of Lemma 1.23 over commensurable lattices, it suffices to prove the equality for
any lattice \( \Lambda \) (compatible with \( \mathcal{H} \)) of our choice. We will prove Theorem 6.1 by the standard ‘deletion-contraction’ argument on arrangement of hyperplanes.

Choose a set \( \Phi^{eq} \) of equations for \( \mathcal{H} \). For \( \phi \in \Phi^{eq} \), we consider the following two arrangements:

- \( \mathcal{H}' = \mathcal{H} \setminus H_\phi \).
- \( \mathcal{H}_0 = \{H \cap H_\phi, H \in \mathcal{H}'\} \), the trace of the arrangement \( \mathcal{H}' \) on \( H_\phi \).

Consider the vector space \( V_0 := V/R_\phi \), let \( p : V \to V_0 \) be the projection. The dual space \( U_0 \) of \( V_0 \) is the hyperplane \( H_\phi \). We now compare the spaces \( S_{\mathcal{H}}, S_{\mathcal{H}_0} \) and \( S_{\mathcal{H}_0} \).

**Definition 6.2.** We say that a function \( f \in \mathcal{M}_{\mathcal{H}} \) has at most a simple pole along the hyperplane \( \phi = 0 \) if \( \phi f \in \mathcal{M}_{\mathcal{H}_0} \). In this case, we define \( \text{res}_\phi f \in \mathcal{M}_{\mathcal{H}_0} \) by \( \text{res}_\phi f = (\phi f)|_{H_\phi} \).

In other words, the meromorphic function \( f \) has at most a simple pole on \( H_\phi \) if the denominator of \( f \) contains the factor \( \phi \) at most once. Then we multiply \( f \) by \( \phi \), eliminating \( \phi \) from the denominator of \( f \), and we can restrict \( \phi f \) to \( \phi = 0 \). This operation kills the functions \( f \) having no poles of \( \phi = 0 \).

If \( f = \frac{1}{\phi} f' \) with \( f' \in \mathcal{M}_{\mathcal{H}_0} \), then

\[
\text{res}_\phi R f = R \text{res}_\phi f.
\] (6.2.1)

This is easy to verify using for example a decomposition of \( f' \) with denominator on a set of independent hyperplanes (see Lemma 1.2).

The map \( \text{res}_\phi \) is well defined on \( S_{\mathcal{H}} \), as elements in \( S_{\mathcal{H}} \) have at most a simple pole on \( \phi = 0 \). It is easy to prove that we have the exact sequence

\[
0 \to S_{\mathcal{H}_0} \overset{i}
\to S_{\mathcal{H}} \overset{\text{res}_\phi}
\to S_{\mathcal{H}_0} \to 0.
\] (6.2.2)

Let \( v \in V_{reg}(\Lambda, \mathcal{H}) \). Its projection \( v_0 = p(v) \) belongs to \( V_{reg}(\Lambda_0, \mathcal{H}_0) \).

**Lemma 6.3.** Let \( v \in V_{reg}(\Lambda, \mathcal{H}) \) and \( f \in S_{\mathcal{H}} \). Then

\[
\text{res}_\phi Z^\Lambda(v)(f) = -Z^{\Lambda_0}(v_0)(\text{res}_\phi f),
\]

with \( v_0 = p(v) \).

**Proof.** We have \( Z^\Lambda(v)(f)(z) = \sum_{\gamma \in \Gamma} f(2i\pi \gamma - z)e^{(v,v_0)2i\pi \gamma - z} \). If \( \gamma \) is such that \( (\phi, \gamma) \neq 0 \), then the term \( f(2i\pi \gamma - z) \) has no pole on \( \phi = 0 \). Thus we obtain, for \( z \in H_\phi \),

\[
\text{res}_\phi Z^\Lambda(v)(f)(z) = \sum_{\gamma \in \Gamma, (\gamma, \phi) = 0} (\phi(z)f(2i\pi \gamma - z)|_{H_\phi})e^{(v_0,2i\pi \gamma - z)}
\]

\[
= -\sum_{\gamma \in \Gamma, (\gamma, \phi) = 0} \phi(2i\pi \gamma - z)f(2i\pi \gamma - z)|_{H_\phi}e^{(v_0,2i\pi \gamma - z)}.
\]

\[\square\]
Lemma 6.4. Let \( g \in \mathcal{R}_H \). Then the following diagram is commutative.
\[
\begin{array}{cccccc}
0 & \longrightarrow & \mathcal{S}_H' & \longrightarrow & \mathcal{S}_H & \longrightarrow & \mathcal{S}_{H_0} & \longrightarrow & 0 \\
\downarrow A(v, g) & & \downarrow A(v, g) & & \downarrow -\lambda(v_0, g_0) & & \downarrow & & \\
0 & \longrightarrow & \mathcal{S}_H' & \longrightarrow & \mathcal{S}_H & \longrightarrow & \mathcal{S}_{H_0} & \longrightarrow & 0 \\
\end{array}
\] (6.4.1)

Proof. Let \( g \in \mathcal{R}_H \), and let \( g_0 \) be its restriction to \( H_0 \). Then the operator \( A(v, g) \) leaves \( \mathcal{S}_H \) stable. If \( F \) has at most a simple pole on \( \phi = 0 \), then \( gF \) also has at most a simple pole on \( \phi = 0 \), as \( g \) has no pole on \( \phi = 0 \). Thus maps in the above diagram are well defined. Its commutativity follows from Lemma 6.3.

We are now ready to prove Theorem 6.1 by induction on the number of hyperplanes in \( H \). If there are less than \( r \) hyperplanes, then \( \mathcal{S}_H = \{0\} \), the generalized function \( \mathcal{B}(H, \Lambda, g) \) is supported on affine walls, so both sides of the equation of Theorem 6.1 vanish.

Assume that \( H \) consists of \( r \) independent hyperplanes. Changing the lattice \( \Lambda \), we may assume that \( \Lambda \) is the lattice generated by the equations \( \phi_k \) of the hyperplanes. Then, the theorem follows from Formula (6.1.2) in the one dimensional case.

Assume that \( H \) has more than \( r \) hyperplanes. Then by Lemma 1.2, we can write a function in \( \mathcal{R}_H \) as a sum of functions \( g \) whose poles lie on an independent subset of hyperplanes of \( H \), thus in number less or equal to \( r \). Thus \( \mathcal{R}_H \) is linearly generated by functions \( g \) such that some equation \( \phi \in \Phi^{\neq} \) is not a pole of \( g \). We consider such a couple \((g, \phi)\) and the arrangements \( \mathcal{H}' \) and \( \mathcal{H}_0 \) associated to \( \mathcal{H} \) by deletion and contraction. The function \( g \) is in \( \mathcal{R}_H' \).

Let \( g_0 \in \mathcal{R}_{H_0} \) be the restriction of \( g \) to \( H_0 \). Thus \( \mathcal{B}(H_0, \Lambda_0, g_0) \) is a generalized function on \( H_0^\circ = V/\mathbb{R}\phi \) and \( p^* \mathcal{B}(H_0, \Lambda_0, g_0) \) is a function on \( V \) (constant in the direction \( \phi \)).

We have the following recurrence relation for the function (eventually generalized) \( \mathcal{B}(H, \Lambda, g) \) associated to an element \( g \in \mathcal{R}_H' \).

Proposition 6.5. If \( g \in \mathcal{R}_H' \), then
\[
\mathcal{B}(H, \Lambda, g) = \mathcal{B}(H', \Lambda, g) - p^* \mathcal{B}(H_0, \Lambda_0, g_0).
\]

This is clear. Indeed the set \( \Gamma_{\text{reg}}(H') \) is larger than \( \Gamma_{\text{reg}}(H) \) as it may contain also elements \( \gamma \) with \( (\gamma, \phi) = 0 \). This additional summation gives rise to the term \( \mathcal{B}(H_0, \Lambda_0, g_0) \).

Let \( v \in V_{\text{reg}}(H, \Lambda) \). As \( P(H, \Lambda, g)(v) \) is the trace of the operator \( A(v, g) \) defined in (6.1.1), the commutativity of the diagram (6.4.1) above implies that
\[
P(H, \Lambda, g)(v) = P(H', \Lambda, g)(v) - P(H_0, \Lambda_0, g_0)(v_0).
\]

Comparing with Proposition 6.5, we see by induction that Szenes formula holds.
[1] Atiyah M. F. and Bott R., The Yang-Mills equations over Riemann surfaces Phil. Trans. R. Soc. London, 308 (1982), 523–615.

[2] Baldoni W. and Vergne M., Residues formulae for volumes and Ehrhart polynomials of convex polytopes, arXiv:math/0103097

[3] Boysal A. and Vergne M., Multiple Bernoulli series, an Euler-MacLaurin formula, and Wall crossings Ann. de l’Ins. Fourier 62 (2012), 821–858.

[4] Brion M. and Vergne M., Arrangement of hyperplanes I: Rational functions and Jeffrey-Kirwan residue. Ann. scient. Éc. Norm. Sup. 32 (1999), 715-741.

[5] Gunnells P.E and Sczech R., Evaluation of Dedekind sums, Eisenstein cocycles, and special values of L-functions, Duke Math. J. 118 no. 2 (2003), 229–260.

[6] Komori Y., Matsumoto K. and Tsumura H., A study of multiple zeta values from the viewpoint of zeta-functions of root systems to appear in Funct. Approx. Comment. Math.

[7] Komori Y., Matsumoto K. and Tsumura H., Multiple zeta values and zeta-functions of root systems Proc. Japan Acad. Ser. A Math. Sci. 87, no. 6, 103–107 (2011).

[8] Komori Y., Matsumoto K. and Tsumura H., On Witten multiple zeta-functions associated with semisimple Lie algebras II J. Math. Soc. Japan Volume 62, Number 2 (2010), 355-394.

[9] Komori Y., Matsumoto, K. and Tsumura, H., On Witten multiple zeta-functions associated with semisimple Lie algebras III(English summary) Multiple Dirichlet series, L-functions and automorphic forms, 223286, Progr. Math., 300, Birkhuser/Springer, New York, 2012.

[10] Orlik P. and Solomon L., Unitary reflection groups and cohomology. Invent. Math. 59 (1980) 7794.

[11] Procesi C. Lie groups, Universitext, Springer.

[12] Szemes A., Iterated Residues and Multiple Bernoulli Polynomials. International Mathematics Research Notices 18, (1998), 937–956.

[13] Szemes A., Residue theorem for rational trigonometric sums and Verlinde’s formula. Duke Math. J. 118 (2003), 189–227.

[14] Teleman C. and Woodward C., The index formula for the moduli of G-bundles on a curve. Ann. of Math. 170 (2009), 495–527.
[15] Tsuchiya A., Ueno K. and Yamada Y., Conformal field theory on universal family of stable curves with gauge symmetries. Adv. Stud. Pure Math. (1989) 19, 459–565.

[16] Witten E., On quantum gauge theories in two dimensions. Commun. Math. Phys. 141 (1991), 153–209.