



The bosonic vertex operator algebra on a genus g Riemann surface

Title	The bosonic vertex operator algebra on a genus g Riemann surface
Author(s)	Tuite, Michael P.;Zuevsky, Alexander
Publication Date	2011-08

The Bosonic Vertex Operator Algebra on a Genus g Riemann Surface

Michael P. Tuite and Alexander Zuevsky*

School of Mathematics, Statistics and Applied Mathematics,
National University of Ireland Galway
University Road, Galway, Ireland.

Abstract

We discuss the partition function for the Heisenberg vertex operator algebra on a genus g Riemann surface formed by sewing g handles to a Riemann sphere. In particular, it is shown how the partition can be computed by means of the MacMahon Master Theorem from classical combinatorics.

1 Introduction

In this paper we briefly sketch recent progress in defining and computing the partition function for the Heisenberg Vertex Operator Algebra (VOA) on a genus g Riemann surface. The partition function and n -point correlation functions are familiar concepts at genus one and have recently been computed on genus two Riemann surfaces formed from sewing tori together [MT1],[MT2]. Here we discuss an alternative approach for computing these objects on a general genus g Riemann surface formed by sewing g handles onto a Riemann sphere. This approach includes the classical Schottky parameterisation and a related simpler canonical parameterisation for which we obtain the partition function for rank 2 Heisenberg VOA in terms of an explicit infinite determinant. This determinant is computed by means of the MacMahon Master Theorem in classical combinatorics [MM].

*Supported by a Science Foundation Ireland Frontiers of Research Grant and by Max-Planck Institut für Mathematik, Bonn

2 A Generalized MacMahon Master Theorem

We begin with a review of the MacMahon Master Theorem and a recent generalization. We will provide a proof of this which gives some flavour of the combinatorial graph theory methods developed to compute higher genus partition functions [MT2], [TZ].

Let $A = (A_{ij})$ be an $n \times n$ matrix indexed by $i, j \in \{1, \dots, n\}$. Consider the cycle decomposition of $\pi \in \Sigma_n$, the symmetric group on $\{1, \dots, n\}$,

$$\pi = \sigma_1 \dots \sigma_{C(\pi)}. \quad (1)$$

The β -extended Permanent of the matrix A is defined by [FZ]

$$\text{perm}_\beta A = \sum_{\pi \in \Sigma_n} \beta^{C(\pi)} \prod_i A_{i\pi(i)}. \quad (2)$$

The standard permanent and determinant are the particular cases:

$$\text{perm } A = \text{perm}_{+1} A, \quad \det A = (-1)^n \text{perm}_{-1} A. \quad (3)$$

Consider a multiset $\{k_1, \dots, k_m\}$ with $1 \leq k_1 \leq \dots \leq k_m \leq n$ i.e. index repetition is allowed. We notate the multiset as the unrestricted partition

$$\mathbf{k} = \{1^{r_1} 2^{r_2} \dots n^{r_n}\}, \quad (4)$$

i.e. the index i occurs $r_i \geq 0$ times and where $m = \sum_{i=1}^n r_i$. Let $A(\mathbf{k})$ denote the $m \times m$ matrix indexed by \mathbf{k} for a given matrix A indexed by $\{1, \dots, n\}$. We now describe a generalisation of the classic MacMahon Master Theorem (MMT) of combinatorics [MM]. Let A be an $n \times n$ matrix indexed by $\{1, \dots, n\}$. Let $A(\mathbf{k})$ denote the $m \times m$ matrix indexed by a multiset \mathbf{k} (4).

Theorem 2.1 (Generalized MMT - Foata and Zeilberger [FZ])

$$\sum_{\mathbf{k}} \frac{\text{perm}_\beta A(\mathbf{k})}{r_1! r_2! \dots r_n!} = \frac{1}{\det(I - A)^\beta}, \quad (5)$$

where the (infinite) sum ranges over all multisets $\mathbf{k} = \{1^{r_1} 2^{r_2} \dots n^{r_n}\}$.

For $\beta = 1$, Theorem 2.1 reduces to the classical MMT [MM]. For $\beta = -1$ we use (3) to find that the sum is restricted to proper subsets of $\{1, 2, \dots, n\}$ resulting in the determinant identity

$$\det(I + B) = \sum_{1 \leq k_1 < \dots < k_m \leq n} \det B(\mathbf{k}),$$

for $B = -A$.

Proof of Theorem 2.1. We use a graph theory method applied in [MT2]. Define a set of oriented graphs Γ with elements γ_π whose vertices are labelled by multisets $\mathbf{k} = \{1^{r_1} \dots n^{r_n}\}$ and directed edges $\{e_{ij}\}$ determined by permutations $\pi \in \Sigma(\mathbf{k})$ as follows

$$e_{ij} = \overset{k_i}{\bullet} \longrightarrow \overset{k_j}{\bullet} \text{ for } k_j = \pi(k_i)$$

Define a β dependent weight for each γ_π

$$w_\beta(e_{ij}) = A_{k_i k_j}, \quad w_\beta(\gamma_\pi) = \beta^{C(\pi)} \prod_{e_{ij} \in \gamma_\pi} w_\beta(e_{ij}), \quad (6)$$

where $C(\pi)$ is the number of disjoint cycles in π . Then we may write

$$\text{perm}_\beta A(\mathbf{k}) = \sum_{\pi \in \Sigma(\mathbf{k})} w_\beta(\gamma_\pi).$$

γ_π is invariant under permutations of the identical labels of \mathbf{k} . Hence the left hand side of (5) can be rewritten as

$$\sum_{\mathbf{k}} \frac{\text{perm}_\beta A(\mathbf{k})}{r_1! r_2! \dots r_n!} = \sum_{\gamma \in \Gamma} \frac{w_\beta(\gamma)}{|\text{Aut}(\gamma)|},$$

where we sum over all inequivalent graphs in Γ . Each $\gamma \in \Gamma$ can be decomposed into disjoint connected cycle graphs $\gamma_\sigma \in \Gamma$

$$\gamma = \gamma_{\sigma_1}^{m_1} \dots \gamma_{\sigma_K}^{m_K}.$$

Each cycle σ corresponds to a disjoint connected cycle graph $\gamma_\sigma \in \Gamma$ with weight

$$w_\beta(\gamma_\pi) = \prod_i w_\beta(\gamma_{\sigma_i})^{m_i}.$$

Furthermore

$$|\text{Aut}(\gamma_\pi)| = \prod_i |\text{Aut}(\gamma_{\sigma_i})|^{m_i} m_i!$$

Let Γ_σ denote the set of inequivalent cycles. Then

$$\begin{aligned} \sum_{g \in \Gamma} \frac{w_\beta(g)}{|\text{Aut}(g)|} &= \prod_{\gamma_\sigma \in \Gamma_\sigma} \sum_{m \geq 0} \frac{w_\beta(\gamma_\sigma)^m}{|\text{Aut}(\gamma_\sigma)|^m m!} \\ &= \exp \left(\sum_{\gamma_\sigma \in \Gamma_\sigma} \frac{w_\beta(\gamma_\sigma)}{|\text{Aut}(\gamma_\sigma)|} \right). \end{aligned} \quad (7)$$

For a cycle σ of order $|\sigma| = r$ then $\text{Aut}(\gamma_\sigma) = \langle \sigma^s \rangle$, a cyclic group of order $|\text{Aut}(\gamma_\sigma)| = \frac{r}{s}$. Using the trace identity

$$\sum_{\gamma_\sigma, |\sigma|=r} s w_\beta(\gamma_\sigma) = \beta \text{Tr}(A^r),$$

we find

$$\begin{aligned} \sum_{\gamma_\sigma \in \Gamma_\sigma} \frac{w_\beta(\gamma_\sigma)}{|\text{Aut}(\gamma_\sigma)|} &= \beta \sum_{r \geq 1} \frac{1}{r} \text{Tr}(A^r) \\ &= -\beta \text{Tr}(\log(I - A)) \\ &= -\beta \log \det(I - A). \end{aligned}$$

Thus

$$\sum_{\mathbf{k}} \frac{\text{perm}_\beta A(\mathbf{k})}{r_1! r_2! \dots r_n!} = \det(I - A)^{-\beta}. \quad \square$$

Define a cycle to be primitive (or rotationless) if $|\text{Aut}(\gamma_\sigma)| = 1$. For a general cycle σ with $|\text{Aut}(\gamma_\sigma)| = s$ we have for $\beta = 1$

$$w_1(\gamma_\sigma) = w_1(\gamma_\rho)^s,$$

for some primitive cycle ρ . Let Γ_ρ denote the set of all primitive cycles. Then

$$\begin{aligned} \sum_{\gamma_\sigma \in \Gamma_\sigma} \frac{w_1(\gamma_\sigma)}{|\text{Aut}(\gamma_\sigma)|} &= \sum_{\gamma_\rho \in \Gamma_\rho} \sum_{s \geq 1} \frac{1}{s} w_1(\gamma_\rho)^s \\ &= - \sum_{\gamma_\rho \in \Gamma_\rho} \log \det(1 - w_1(\gamma_\rho)). \end{aligned}$$

Combining this with (7) implies [MT2]

Theorem 2.2

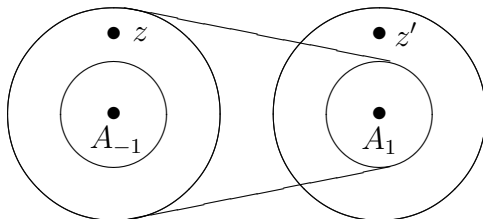
$$\det(I - A) = \prod_{\gamma_\rho \in \Gamma_\rho} (1 - w_1(\gamma_\rho)).$$

3 Riemann Surfaces from a Sewn Sphere

3.1 The Riemann torus

Consider the construction of a torus by sewing a handle to the Riemann sphere $\hat{\mathbb{C}}$ by identifying annular regions centred at $A_{\pm 1} \in \hat{\mathbb{C}}$ via a sewing condition with complex sewing parameter ρ

$$(z - A_{-1})(z' - A_1) = \rho. \quad (8)$$



We call ρ, A_{\pm} canonical parameters. The annuli do not intersect provided

$$|\rho| < \frac{1}{4}|A_{-1} - A_1|^2. \quad (9)$$

Inequivalent tori depend only on

$$\chi = -\frac{\rho}{(A_{-1} - A_1)^2}, \quad (10)$$

where (9) implies $|\chi| < \frac{1}{4}$ [MT1].

Equivalently, we define $q, a_{\pm 1}$, known as Schottky parameters, by

$$\begin{aligned} a_i &= \frac{A_i + qA_{-i}}{1 + q}, \\ \frac{q}{(1 + q)^2} &= \chi, \end{aligned} \quad (11)$$

for $i = \pm 1$. Inequivalent tori depend only on q with $|q| < 1$. The canonical sewing condition (8) is equivalent to:

$$\left(\frac{z - a_{-1}}{z - a_1}\right) \left(\frac{z' - a_1}{z' - a_{-1}}\right) = q. \quad (12)$$

Inverting (11) we find that $q = C(\chi)$ for Catalan series

$$C(\chi) = \frac{1 - (1 - 4\chi)^{1/2}}{2\chi} - 1 = \sum_{n \geq 1} \frac{1}{n} \binom{2n}{n+1} \chi^n. \quad (13)$$

3.2 Genus g Riemann Surfaces

We may similarly construct a general genus g Riemann surface by identifying g pairs of annuli centred at $A_{\pm i} \in \hat{\mathbb{C}}$ for $i = 1, \dots, g$ and sewing parameters ρ_i satisfying

$$(z - A_{-i})(z' - A_i) = \rho_i, \quad (14)$$

provided no two annuli intersect. Equivalently, for $i = 1, \dots, g$ we define Schottky parameters $a_{\pm i}, q_i$ by

$$\begin{aligned} a_{\pm i} &= \frac{A_{\pm i} + q_i A_{\mp i}}{1 + q_i}, \\ \frac{q_i}{(1 + q_i)^2} &= -\frac{\rho_i}{(A_{-i} - A_i)^2}, \end{aligned} \quad (15)$$

where $|q_i| < 1$ is again related to the Catalan series (13)

$$q_i = C(\chi_i), \quad \chi_i = -\frac{\rho_i}{(A_i - A_{-i})^2}.$$

The canonical sewing condition can then be rewritten as a standard Schottky sewing condition:

$$\left(\frac{z - a_{-i}}{z - a_i}\right) \left(\frac{z' - a_i}{z' - a_{-i}}\right) = q_i. \quad (16)$$

The Schottky sewing condition (16) determines a Möbius map $z' = \gamma_i(z)$ where

$$\gamma_i = \sigma_i^{-1} \begin{pmatrix} q_i & 0 \\ 0 & 1 \end{pmatrix} \sigma_i, \quad (17)$$

for Möbius map

$$\sigma_i(z) = \frac{z - a_i}{z - a_{-i}}. \quad (18)$$

We define the Schottky group $\Gamma = \langle \gamma_i \rangle$ as the Kleinian group freely generated by γ_i for $i = 1, \dots, g$.

One can find explicit formulas for various objects defined on the Riemann surface such as the bilinear form of the second kind, a basis of g holomorphic 1-forms and the genus g period matrix in terms of either the Canonical or Schottky parametrizations [TZ]. In the Schottky case, these involve sums or products over the Schottky group or subsets thereof.

4 Vertex Operator Algebras

Consider a simple VOA with \mathbb{Z} -graded vector space $V = \bigoplus_{n \geq 0} V^{(n)}$ and local vertex operators $Y(a, z) = \sum_{n \in \mathbb{Z}} a_n z^{-n-1}$ for $a \in V$ e.g. [Ka],[FLM],[MN],[MT3]. We assume that V is of CFT type (i.e. $V_0 = \mathbb{C}\mathbf{1}$) with a unique symmetric invertible invariant bilinear form $\langle \cdot, \cdot \rangle$ with normalization $\langle \mathbf{1}, \mathbf{1} \rangle = 1$ where [FHL],[Li]

$$\langle Y(a, z)b, c \rangle = \langle b, Y(e^{zL_1}(-\frac{1}{z^2})^{L_0}a, \frac{1}{z})c \rangle \quad (19)$$

For a V -basis $\{u^\alpha\}$, we let $\{\bar{u}^\alpha\}$ denote the dual basis. If $a \in V^{(k)}$ is quasi-primary ($L_1 a = 0$) then (19) implies

$$\langle a_n b, c \rangle = (-1)^k \langle b, a_{2k-n-2} c \rangle.$$

In particular:

$$\begin{aligned} \langle a_n b, c \rangle &= -\langle b, a_{-n} c \rangle \text{ for } a \in V^{(1)} \\ \langle L_n b, c \rangle &= \langle b, L_{-n} c \rangle \text{ for } \omega \in V^{(2)}, \end{aligned} \quad (20)$$

so that b, c with unequal weights are orthogonal.

4.1 Genus Zero Correlation Functions

For $u_1, u_2, \dots, u_n \in V$ define the n -point (correlation) function by

$$\langle \mathbf{1}, Y(u_1, z_1)Y(u_2, z_2) \dots Y(u_n, z_n)\mathbf{1} \rangle. \quad (21)$$

The locality property of vertex operators implies that this formal expression (21) coincides with the analytic expansion of a rational function of z_1, z_2, \dots, z_n in the domain $|z_1| > |z_2| > \dots > |z_n|$. Thus the n -point function can be taken to be a rational function of $z_1, z_2, \dots, z_n \in \hat{\mathbb{C}}$, the Riemann sphere in the domain. For example [HT]

Theorem 4.1 *For a VOA of central charge C , the Virasoro n -point function is a β -extended permanent*

$$\langle \mathbf{1}, Y(\omega, z_1) \dots Y(\omega, z_n) \mathbf{1} \rangle = \text{perm}_{\frac{C}{2}} B,$$

for $B_{ij} = \frac{1}{(z_i - z_j)^2}$, $i \neq j$ and $B_{ii} = 0$.

4.2 Rank Two Heisenberg VOA M_2

Consider the VOA generated by two Heisenberg vectors $a^\pm \in V^{(1)}$ whose modes satisfy non-trivial commutator

$$[a_m^+, a_n^-] = m\delta_{m,-n}. \quad (22)$$

V has a Fock basis spanned by

$$a_{\mathbf{k}, \mathbf{l}} = a_{-k_1}^+ \dots a_{-k_m}^+ a_{-l_1}^- \dots a_{-l_n}^- \mathbf{1}, \quad (23)$$

labelled by a multisets $\mathbf{k} = \{k_1, \dots, k_m\} = \{1^{r_1}, 2^{r_2}, \dots\}$ and $\mathbf{l} = \{l_1, \dots, l_n\} = \{1^{s_1}, 2^{s_2}, \dots\}$. The Fock vectors are orthogonal with respect to the invariant bilinear form with dual basis

$$\bar{a}_{\mathbf{k}, \mathbf{l}} = \prod_i \frac{1}{i^{r_i} r_i!} \prod_j \frac{1}{j^{s_j} s_j!} a_{\mathbf{l}, \mathbf{k}}. \quad (24)$$

The basic Heisenberg 2-point function is

$$\langle \mathbf{1}, Y(a^+, x) Y(a^-, y) \mathbf{1} \rangle = \frac{1}{(x - y)^2}. \quad (25)$$

This function provides all the necessary data for computing the Heisenberg partition and correlation functions on a genus g surface! Thus the general rank 2 Heisenberg $2n$ -point function is

$$\langle \mathbf{1}, Y(a^+, x_1) \dots Y(a^+, x_n) Y(a^-, y_1) \dots Y(a^-, y_n) \mathbf{1} \rangle = \text{perm} \left(\frac{1}{(x_i - y_j)^2} \right). \quad (26)$$

This is a generating function for all rank two Heisenberg correlation functions by associativity of the VOA.

Let $x_{-i} = x - A_{-i}$ and $y_j = y - A_j$ be local coordinates in the neighborhood of canonical sewing parameters A_{-i}, A_j for $i, j \in \{\pm 1, \dots, \pm g\}$ with $i \neq -j$. The 2-point function has expansion

$$\frac{1}{(x-y)^2} = \sum_{k, l \geq 1} (-1)^{k+l} \frac{(k+l-1)!}{(k-1)!(l-1)!} \frac{x_{-i}^{k-1} y_j^{l-1}}{(A_{-i} - A_j)^{k+l}}.$$

Define the canonical moment matrix R^{Can} , an infinite matrix indexed by $k, l = 1, 2, \dots$ and $i, j \in \{\pm 1, \dots, \pm g\}$ where

$$R_{ij}^{\text{Can}}(k, l) = \begin{cases} \frac{(-1)^k \rho_i^{k/2} \rho_j^{l/2}}{\sqrt{kl}} \frac{(k+l-1)!}{(k-1)!(l-1)!} \frac{1}{(A_{-i} - A_j)^{k+l}}, & i \neq -j \\ 0, & i = -j \end{cases} \quad (27)$$

$(I - R^{\text{Can}})^{-1}$ plays a central role in computing the genus g period matrix and other structures.

We similarly have expansions in the Schottky parameters. Let

$$x_{-i} = \sigma_{-i}(x) = \frac{x - a_{-i}}{x - a_i} \quad (28)$$

$$y_j = \sigma_j(x) = \frac{y - a_j}{y - a_{-j}} \quad (29)$$

for $i, j \in \{1, \dots, g\}$ be local coordinates in the neighborhood of the Schottky points a_{-i} and a_j for $i \neq -j$. The 2-point function expansion leads to the Schottky moment matrix with

$$R_{ij}^{\text{Sch}}(k, l) = \begin{cases} q_i^{k/2} q_j^{l/2} D(k, l) (\sigma_i \sigma_j^{-1}), & i \neq -j \\ 0, & i = -j \end{cases} \quad (30)$$

where for $\gamma \in SL(2, \mathbb{C})$

$$D(k, l)(\gamma) = \frac{1}{l!} \sqrt{\frac{l}{k}} \partial_z^l (\gamma(z)^k) |_{z=0}. \quad (31)$$

D is an $SL(2, \mathbb{C})$ representation [Mo]. Then it follows

$$\sum_{s \geq 1} R_{ij}^{\text{Sch}}(r, s) R_{jk}^{\text{Sch}}(s, t) = q_i^{r/2} q_k^{t/2} D(r, t) (\sigma_i \gamma_j \sigma_k^{-1}), \quad (32)$$

for Schottky generator (17).

4.3 The Genus g Partition Function - Canonical Parameters

We now define the genus g partition function for a VOA V in the canonical sewing scheme in terms of genus zero $2g$ -point correlation functions as follows:

$$Z_V^{(g)}(\rho_i, A_{\pm i}) = \langle \mathbf{1}, \prod_{i=1}^g \sum_{n_i \geq 0} \rho_i^{n_i} \sum_{v_i \in V^{(n)}} Y(v_i, A_{-i}) Y(\bar{v}_i, A_i) \mathbf{1} \rangle, \quad (33)$$

where \bar{v}_i is dual to v_i .

For genus one this reverts to the standard definition:

Theorem 4.2 (Mason and T.)

$$Z_V^{(1)}(\rho, A_{\pm 1}) = \text{Tr}_V(q^{L_0})$$

where $q = C(\chi)$, the Catalan series for $\chi = -\frac{\rho}{(A_{-1}-A_1)^2}$.

4.4 $Z_{M_2}^{(g)}(\rho_i, A_{\pm i})$ for Heisenberg VOA M_2

The genus g partition function can be computed for the rank 2 Heisenberg VOA by means of the MacMahon Master Theorem where, schematically, we have:

Sum over g Fock bases	→	Sum over multisets
$2g$ -point function	→	Permanent of matrix
Dual vector factorials	→	Multiset factorials
ρ_i and other dual vector factors	→	Absorbed into matrix definition

We then find that [TZ]

Theorem 4.3

$$Z_{M_2}^{(g)}(\rho_i, A_{\pm i}) = \frac{1}{\det(I - R^{\text{Can}})},$$

where R^{Can} is the canonical moment matrix. Furthermore, $\det(I - R^{\text{Can}})$ is holomorphic and non-vanishing. In general, the genus g Heisenberg generating function is expressed in terms of a permanent of genus g bilinear forms of the second kind.

We may repeat this by using an alternative definition of the genus g partition function in terms of Schottky parameters account must be taken of the Möbius maps σ_i of (18). We then find [TZ]

Theorem 4.4 *The genus g partition function is*

$$Z_{M_2}^{(g)}(q_i, a_{\pm i}) = \frac{1}{\det(I - R^{\text{Sch}})},$$

where R^{Sch} is the Schottky moment matrix. Furthermore, $\det(I - R^{\text{Sch}})$ is holomorphic and non-vanishing and the genus g Heisenberg generating function is expressed in terms of a permanent of genus g bilinear forms of the second kind.

Conjecture: $\det(I - R^{\text{Can}}) = \det(I - R^{\text{Sch}})$. This is true for $g = 1$ [MT2].

4.5 The Montonen-Zograf Product Formula

$\det(I - R^{\text{Sch}})$ can be also re-expressed in terms of an infinite product formula originally calculated in physics by Montonen in 1974 [Mo]. A similar product formula was subsequently found by Zograf [Z]. This has been recently related by McIntyre and Takhtajan [McT] to Mumford's theorem concerning the absence of a global section on moduli space for the canonical line bundle [Mu].

Recall that $R_{ij}^{\text{Sch}}(k, l)$ is expressed in terms of an $SL(2, \mathbb{C})$ representation D . This leads to

$$\det(I - R^{\text{Sch}}) = \prod_{m \geq 1} \prod_{\gamma^\alpha \in \Gamma} (1 - q_\alpha^m), \quad (34)$$

where the inner product ranges over the primitive elements γ^α of the Schottky group Γ i.e. $\gamma^\alpha \neq \gamma^k$ for any $\gamma \in \Gamma$ for $k > 1$. Each such element has a multiplier q_α where

$$\gamma^\alpha \sim \begin{pmatrix} q_\alpha & 0 \\ 0 & 1 \end{pmatrix}. \quad (35)$$

References

- [FZ] Foata, D. and Zeilberger, D.: Laguerre polynomials, weighted derangements and positivity, *SIAM J. Discrete Math.* **1** (1988), 425–433.
- [FHL] Frenkel, I., Huang, Y. and Lepowsky, J.: On axiomatic approaches to vertex operator algebras and modules, *Mem.Amer.Math.Soc.* **104**, (1993).
- [FLM] Frenkel, I., Lepowsky, J. and Meurman, A.: *Vertex operator algebras and the Monster*, (Academic Press, New York, 1988).
- [HT] Hurley, D. and Tuite, M.P.: Virasoro correlation functions, to appear.
- [Ka] Kac, V.: *Vertex Operator Algebras for Beginners*, University Lecture Series, Vol. 10, (AMS 1998).
- [Li] Li, H.: Symmetric invariant bilinear forms on vertex operator algebras, *J.Pure.Appl.Alg.* **96** (1994), 279–297.
- [McT] McIntyre, A. and Takhtajan, L.A.: Holomorphic factorization of determinants of Laplacians on Riemann surfaces and higher genus generalization of Kronecker’s first limit formula, *GAFSA, Geom. funct. anal.* **16** (2006), 1291–1323.
- [MM] MacMahon, P.A.: *Combinatory Analysis*, Vol. 1, Cambridge University Press, (Cambridge 1915); reprinted by Chelsea (New York, 1955).
- [MN] Matsuo, A. and Nagatomo, K.: Axioms for a vertex algebra and the locality of quantum fields, *Math.Soc.Jap.Mem.*, **4** (1999).
- [Mo] Montonen, C.: Multiloop amplitudes in additive dual-resonance models, *Nuovo Cimento* **19** (1974), 69–89.
- [MT1] Mason, G. and Tuite, M.P.: On genus two Riemann surfaces formed from sewn tori, *Commun.Math.Phys.* **270** (2007), 587–634.
- [MT2] Mason, G. and Tuite, M.P.: Free bosonic vertex operator algebras on genus two Riemann surfaces I, *Commun.Math.Phys.* **300** (2010) 673–713.
- [MT3] Mason, G. and Tuite, M.P.: Vertex operators and modular forms, *A Window into Zeta and Modular Physics* eds. K. Kirsten and F. Williams, MSRI Publications **57** 183–278, Cambridge University Press, (Cambridge, 2010).

- [Mu] Mumford, D.: Stability of Projective Varieties, L.Ens.Math. **23** (1977), 39–110.
- [TZ] Tuite, M.P. and Zuevsky, A.: The Heisenberg vertex operator algebra on a genus g Riemann surface, to appear.
- [Z] Zograf, P.G.: Liouville action on moduli spaces and uniformization of degenerate Riemann surfaces, (Russian) Algebra i Analiz **1** (1989) 136–160; translation in Leningrad Math. J. **1** (1990), 941–965.