

Theta Functions, Kronecker Functions, and Bilinear Relations

Artyom Lisitsyn

Riemann Surfaces
in Mathematical Physics

Outline

1. Abel's map
2. Theta functions
3. Kronecker function
4. Striving for higher genus

Outline

1. Abel's map

2. Theta functions

3. Kronecker function

4. Striving for higher genus

Holomorphic Differentials

Definition and existence of holomorphic differentials

Definition: $\omega = f_\alpha dz_\alpha = f_\beta dz_\beta$, f holomorphic

Existence: $\dim \mathcal{H}^1 = g$ (genus of compact Riemann surface)

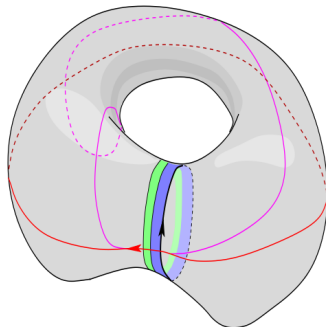
Proof outline:

- $\dim \mathcal{H}^1 \leq \# \text{ of a-cycles} = g$
- $\# \text{ of harmonic differentials} = \dim H \geq 2g$
- $h = f dz + g d\bar{z} \implies \dim H = 2 \dim \mathcal{H}^1$
- $g \leq \dim \mathcal{H}^1 \leq g \implies \dim \mathcal{H}^1 = g$

Normalization & period matrix:

$$\int_{a_i} \omega_j = \delta_{ij}$$

$$\int_{b_i} \omega_j = \tau_{ij}$$



Regions used to define harmonic differentials
Bertola 2006

Abel's map

Bertola 2006 Section 4.2

Formal definition of Abel's map

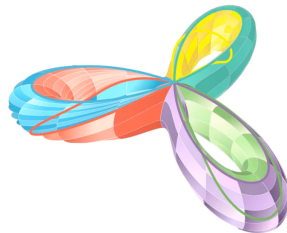
For a particular choice of a point P_0 on the fundamental domain \mathcal{L} , using the normalized harmonic differentials ω_i , we have Abel's map

$$\mathbf{u} : \mathcal{L} \mapsto \mathbb{C}^g, \quad P \mapsto \begin{pmatrix} \int_{P_0}^P \omega_1 \\ \vdots \\ \int_{P_0}^P \omega_g \end{pmatrix}$$

Analytic continuation beyond the fundamental domain:

$$\mathbf{u}(P + a_i) = \mathbf{u}(P) + \begin{pmatrix} \int_{a_i} \omega_1 \\ \vdots \end{pmatrix} = \mathbf{u}(P) + \begin{pmatrix} \delta_{i1} \\ \vdots \end{pmatrix}$$

$$\mathbf{u}(P + b_i) = \mathbf{u}(P) + \begin{pmatrix} \tau_{i1} \\ \vdots \end{pmatrix}$$



Genus 3 surface

Abel's map

Bertola 2006 Section 4.2

Formal definition of Abel's map

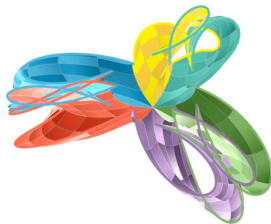
For a particular choice of a point P_0 on the fundamental domain \mathcal{L} , using the normalized harmonic differentials ω_i , we have Abel's map

$$\mathbf{u} : \mathcal{L} \mapsto \mathbb{C}^g, \quad P \mapsto \begin{pmatrix} \int_{P_0}^P \omega_1 \\ \vdots \\ \int_{P_0}^P \omega_g \end{pmatrix}$$

Analytic continuation beyond the fundamental domain:

$$\mathbf{u}(P + a_i) = \mathbf{u}(P) + \begin{pmatrix} \int_{a_i} \omega_1 \\ \vdots \end{pmatrix} = \mathbf{u}(P) + \begin{pmatrix} \delta_{i1} \\ \vdots \end{pmatrix}$$

$$\mathbf{u}(P + b_i) = \mathbf{u}(P) + \begin{pmatrix} \tau_{i1} \\ \vdots \end{pmatrix}$$



Unfolding Genus 3 Surface

Abel's map

Bertola 2006 Section 4.2

Formal definition of Abel's map

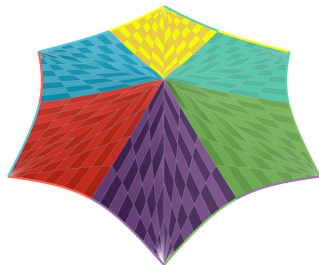
For a particular choice of a point P_0 on the fundamental domain \mathcal{L} , using the normalized harmonic differentials ω_i , we have Abel's map

$$\mathbf{u} : \mathcal{L} \mapsto \mathbb{C}^g, \quad P \mapsto \begin{pmatrix} \int_{P_0}^P \omega_1 \\ \vdots \\ \int_{P_0}^P \omega_g \end{pmatrix}$$

Analytic continuation beyond the fundamental domain:

$$\mathbf{u}(P + a_i) = \mathbf{u}(P) + \begin{pmatrix} \int_{a_i} \omega_1 \\ \vdots \end{pmatrix} = \mathbf{u}(P) + \begin{pmatrix} \delta_{i1} \\ \vdots \end{pmatrix}$$

$$\mathbf{u}(P + b_i) = \mathbf{u}(P) + \begin{pmatrix} \tau_{i1} \\ \vdots \end{pmatrix}$$



Genus 3 fundamental domain

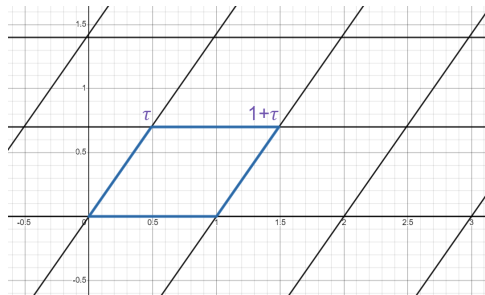
Abel's map at genus 1

Appropriate differential

$$\omega = dz$$

Abel's map

$$\mathbf{u}(z) = \int_0^z \omega = z$$



Fundamental domain and continuation at genus 1

What about higher genus?

- How do we represent the fundamental domain?
- What choice of differentials can we make?
- What consequences does this have for Abel's map?

Outline

1. Abel's map

2. Theta functions

3. Kronecker function

4. Striving for higher genus

Theta functions

Bertola 2006 Section 5.1

Definition of the Theta function

Given a symmetric matrix τ with positive definite imaginary part, the Theta function is

$$\Theta(\vec{z}, \tau) := \sum_{\vec{n} \in \mathbb{Z}^g} \mathbf{e} \left(\frac{1}{2} \vec{n}^T \tau \vec{n} + \vec{n}^T \vec{z} \right) \quad , \quad \mathbf{e}(z) = \exp(2\pi i z)$$

Properties: For $\vec{\lambda} \in \mathbb{Z}^g$

$$\Theta(-\vec{z}) \stackrel{\vec{n} \mapsto -\vec{n}}{=} \Theta(\vec{z})$$

$$\Theta(\vec{z} + \vec{\lambda}) = \sum_{\vec{n} \in \mathbb{Z}^g} \cancel{\mathbf{e}(\vec{n}^T \vec{\lambda})} \overset{1}{\mathbf{e}(\dots)} = \Theta(\vec{z})$$

$$\Theta(\vec{z} + \tau \vec{\lambda}) = \left[\begin{array}{c} \text{shift } \vec{n} \\ \text{use } \tau \text{ symmetry} \end{array} \right] = \mathbf{e} \left(-\frac{1}{2} \vec{\lambda}^T \tau \vec{\lambda} - \vec{\lambda}^T \vec{z} \right) \Theta(\vec{z})$$

Theta function on a compact Riemann surface

Bertola 2006 Section 5.2

Definition of Theta function on a compact Riemann surface

For a compact Riemann surface \mathcal{M} of genus g , with period matrix τ and Abel's map \mathbf{u} , we can identify

$$\begin{aligned}\theta : \mathcal{M} &\mapsto \mathbb{C} \\ P &\mapsto \Theta(\mathbf{u}(P))\end{aligned}$$

Properties:

$$\theta(P + a_i) = \theta(P)$$

$$\theta(P + b_i) = \mathbf{e} \left(-\frac{1}{2} \tau_{ii} - \mathbf{u}_i(P) \right) \theta(P)$$

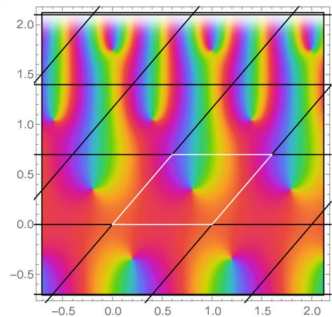
Theta function at genus 1

$$\theta(z) = \sum_{n \in \mathbb{Z}} \mathbf{e}\left(\frac{1}{2}n^2\tau + nz\right)$$

$$\theta(z) = \theta(-z)$$

$$\theta(z+1) = \theta(z)$$

$$\theta(z+\tau) = \mathbf{e}\left(-\frac{1}{2}\tau - \xi\right)\theta(z)$$



Theta function for $\tau = 0.7 + 0.6i$
Chan 2022

What about higher genus?

- What does the Theta function look like at higher genus?

Theta function with characteristics

Bertola 2006 Section 5.1

Definition of Theta function with characteristics

Consider vectors $\epsilon, \epsilon' \in \mathbb{R}^g$. We can then define the Theta function with characteristics ϵ, ϵ' as

$$\Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z}) := \mathbf{e} \left(\frac{1}{8} \epsilon^T \tau \epsilon + \frac{1}{2} \epsilon^T \vec{z} + \frac{1}{4} \epsilon^T \epsilon' \right) \Theta \left(\vec{z} + \frac{\epsilon'}{2} + \frac{\tau \epsilon}{2} \right) = \left[\begin{array}{l} \vec{n} \mapsto \vec{n} + \epsilon \\ \vec{z} \mapsto \vec{z} + \epsilon' \end{array} \right] \sum_{\vec{n}} \mathbf{e}(\dots)$$

Properties:

$$\Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z} + \vec{\alpha} + \tau \vec{\beta}) = \mathbf{e} \left(\frac{1}{2} (\epsilon^T \vec{\alpha} - \vec{\beta}^T \epsilon') - \frac{1}{2} \beta^T \tau \beta - \vec{\beta}^T \vec{z} \right) \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z})$$

$$\Theta \begin{bmatrix} \epsilon + 2\eta \\ \epsilon' + 2\eta' \end{bmatrix} (\vec{z}) = \exp(\pi i \epsilon^T \eta') \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z}) \quad , \quad \eta, \eta' \in \mathbb{Z}^g$$

$$\Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (-\vec{z}) = \exp(\pi i \epsilon^T \epsilon') \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z}) \quad , \quad \epsilon, \epsilon' \in \mathbb{Z}^g$$

Odd theta functions and zeros

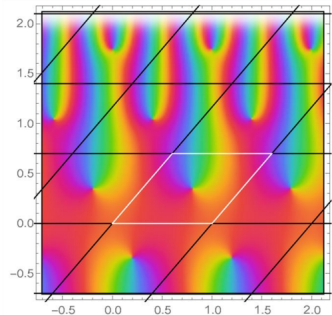
$$\epsilon, \epsilon' \in \mathbb{Z}^g, \quad \epsilon^T \epsilon' \text{ is odd}$$

$$\Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (-\vec{z}) = \exp(\pi i \epsilon^T \epsilon') \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z})$$

$$\Rightarrow \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{z}) = -\Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (-\vec{z})$$

$$\Rightarrow \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (0) = \Theta \begin{bmatrix} \epsilon \\ \epsilon' \end{bmatrix} (\vec{\alpha} + \tau \vec{\beta}) = 0$$

$$\Rightarrow \Theta \left(\frac{\epsilon'}{2} + \frac{\tau \epsilon}{2} \right) = 0$$



Theta function for $\tau = 0.7 + 0.6i$
Chan 2022

What about higher genus?

- Which of the zeros located by odd characteristics are actually reached by Abel's map on compact Riemann surfaces of higher genus?

Odd theta function at genus 1

Odd theta function at genus 1

We define

$$\theta_1(z) = -\theta \begin{bmatrix} 1 \\ 1 \end{bmatrix} (z)$$

It has equivalent definition

$$\theta_1(z) = 2iq^{1/8} \sin(\pi z) \prod_j (1 - q^j)(1 - wq^j)(1 - w^{-1}q^j) \quad , \quad q = e(\tau), w = ez$$

Jacobi Triple Product:

$$f(x, y) = \prod_{j>0} (1 - x^{2m})(1 + x^{2m-1}y^2)(1 + x^{2m-1}y^{-2})$$

$$f(x, xy) = \prod_{j>0} (1 - x^{2m})(1 + x^{2m+1}y^2)(1 + x^{2m-3}y^{-2}) = \frac{1 + x^{-1}y^{-2}}{1 + xy^2} f(x, y) = x^{-1}y^{-2} f(x, y)$$

Odd theta function at genus 1

$$f(x, y) = \prod_{j>0} (1 - x^{2j})(1 + x^{2j-1}y^2)(1 + x^{2j-1}y^{-2})$$

$$f(x, xy) = \prod_{j>0} (1 - x^{2j})(1 + x^{2j+1}y^2)(1 + x^{2j-3}y^{-2}) = \frac{1 + x^{-1}y^{-2}}{(1 + xy^2)} f(x, y) = x^{-1}y^{-2} f(x, y)$$

$$f(x, y) = \sum_{n=-\infty}^{\infty} c_n(x) y^{2n} \implies f(x, y) = xy^2 f(x, xy) = \sum_n c_n(x) x^{2n+1} y^{2n+2}$$

$$\implies c_{n+1}(x) = x^{2n+1} c_n(x) \implies c_n(x) = c_0(x) x^{n^2} \implies f(x, y) = c_0(x) \sum_n x^{n^2} y^{2n}$$

This relates the two forms of the theta function : $\prod_j (1 - q^j)(1 - wq^j)(1 - w^{-1}q^j) \simeq \sum_n \mathbf{e}(\tau)^{n^2} \mathbf{e}(z)^n$

What about higher genus?

- Are there similar Jacobi formulas for higher genus theta functions?

(Application) Decomposing meromorphic functions

Chan 2022 Section 3.4 & Bertola 2006 Chapter 6

Rough outline of how to reproduce a function with divisor $(f) = \sum n_i P_i$

$$\left[\begin{array}{c} \text{Find function } t(z) \\ \text{with known simple zero} \end{array} \right] \rightarrow \left[\begin{array}{c} g(z) = \prod t(P - P_i)^{n_i} \\ \text{respecting possible periodicity} \end{array} \right] \rightarrow \left(\frac{f}{g} \right) = \emptyset \rightarrow \frac{f}{g} = \text{const.}$$

Recall that $\deg((f)) = \sum n_i = 0$ for meromorphic functions, so extra factors can easily cancel.

Genus 0:

- $f(z) = C \prod (z - z_i)^{n_i}$

Genus > 0 :

- $\Theta(\xi) = 0$
- $g_{P'} : P \mapsto \Theta(\mathbf{u}(P) - \mathbf{u}(P') + \xi)$
- $f(P) = C \prod (g_{P_i}(P))^{n_i}$

Genus 1:

- Decompose $z_i = \frac{b_i}{2} + \tau \frac{a_i}{2}$
- $f(z) = C \prod \left(\theta \begin{bmatrix} a_i \\ b_i \end{bmatrix} (z) \right)^{n_i}$

Outline

1. Abel's map

2. Theta functions

3. Kronecker function

4. Striving for higher genus

Analogous function for Genus 0

$$F(z, \alpha) = \frac{(z + \alpha)}{(z)(\alpha)}$$

↓

$$\alpha F(z, \alpha) dz = \sum_{n=0,1} g^{(n)}(z) dz = dz + \frac{dz}{z}$$

↓

use differentials to calculate multiple polylogarithms

Kronecker function at Genus 1

Elliptic version of what was shown above:

$$\frac{\theta_1(z + \alpha)}{\theta_1(z)\theta_1(\alpha)}$$

Kronecker function

Brown and Levin 2013 Section 3.4

Definitions of the Kronecker function

The Kronecker function $F(z, \alpha, \tau)$ has equivalent definitions

1. In terms of the odd theta function

$$\frac{\theta_1'(0)\theta_1(z+\alpha)}{\theta_1(z)\theta_1(\alpha)}$$

2. In terms of a sum over exponentials $F(\xi, \alpha, \tau)$

$$-2\pi i \left(\frac{z}{1-z} + \frac{1}{1-w} + \sum_{m,n>0} (z^m w^n - z^{-m} w^{-n}) q^{mn} \right), \quad \begin{pmatrix} z \\ w \\ q \end{pmatrix} = \mathbf{e} \begin{pmatrix} \xi \\ \alpha \\ \tau \end{pmatrix}$$

3. In terms of a sum over Eisenstein functions and series

$$\frac{1}{\alpha} \exp \left(- \sum_{j>0} \frac{(-\alpha)^j}{j} (E_j(z, \tau) - e_j(\tau)) \right)$$

Properties of the Kronecker function

Brown and Levin 2013 Section 3.4

What about higher genus?

- How can we define the Kronecker function at higher genus?

Periodicity Properties:

$$F(z+1, \alpha) = \frac{\theta_1'(0)\theta_1(z+\alpha+1)}{\theta_1(z+1)\theta_1(\alpha)} = F(z, \alpha)$$
$$F(z+\tau, \alpha) = \frac{\theta_1'(0)\theta_1(z+\alpha+\tau)}{\theta_1(z+\tau)\theta_1(\alpha)} = \frac{e(-z-\alpha)}{e(-z)} F(z, \alpha)$$

The Fay Relation

$$F(z_1, \alpha_1)F(z_2, \alpha_2) = F(z_1, \alpha_1 + \alpha_2)F(z_2 - z_1, \alpha_2) + F(z_2, \alpha_1 + \alpha_2)F(z_1 - z_2, \alpha_1)$$

Setup for derivation of the Fay relation

Matthes 2019

$$F(z_1, \alpha_1)F(z_2, \alpha_2) = F(z_1, \alpha_1 + \alpha_2)F(z_2 - z_1, \alpha_2) + F(z_2, \alpha_1 + \alpha_2)F(z_1 - z_2, \alpha_1)$$

↓ rewrite using Theta functions ↓

$$\frac{\theta_1(z_1 + \alpha_1)\theta_1(z_2 + \alpha_2)}{\theta_1(z_1)\theta_1(\alpha_1)\theta_1(z_2)\theta_1(\alpha_2)} = \frac{\theta_1(z_1 + \alpha_1 + \alpha_2)\theta_1(z_2 - z_1 + \alpha_2)}{\theta_1(z_1)\theta_1(\alpha_1 + \alpha_2)\theta_1(z_2 - z_1)\theta_1(\alpha_2)} + \frac{\theta_1(z_1 + \alpha_1 + \alpha_2)\theta_1(z_1 - z_2 + \alpha_1)}{\theta_1(z_1)\theta_1(\alpha_1 + \alpha_2)\theta_1(z_1 - z_2)\theta_1(\alpha_1)}$$

↓ multiply common denominator and relabel ↓

$$\begin{aligned} &\theta_1(\alpha_0)\theta_1(\beta_0)\theta_1(\alpha_2 + \beta_1)\theta_1(\alpha_2 - \beta_1) + \\ &\theta_1(\alpha_1)\theta_1(\beta_1)\theta_1(\alpha_0 + \beta_2)\theta_1(\alpha_0 - \beta_2) + \\ &\theta_1(\alpha_2)\theta_1(\beta_2)\theta_1(\alpha_1 + \beta_0)\theta_1(\alpha_1 - \beta_0) = 0 \end{aligned}$$

↓ long process involving odd and even theta functions at genus 1 ↓

...

What about higher genus?

- What does the Fay identity look like at higher genus when theta functions are more complicated?

Differentials from the Kronecker function

Broedel et al. 2015 Section 3.3.3

$$\alpha F(z, \alpha) dz = \sum_{n=0}^{\infty} g^{(n)}(z) dz \alpha^n$$

$$g^{(0)}(z) = 1$$

$$g^{(1)}(z) = \pi \cot(\pi z) + 4\pi \sum_{m=1}^{\infty} \sin(2\pi m z) \sum_{n=1}^{\infty} q^{mn}$$

$$g^{(2)}(z) = -2\zeta_2 + 8\pi^2 \sum_{m=1}^{\infty} \cos(2\pi m z) \sum_{n=1}^{\infty} n q^{mn}$$

$$\vdots$$

$$\boxed{g^{(n)}(-z) = (-1)^n g^{(n)}(z)}$$

Independence of the differentials

Brown and Levin 2013 Lemma 8

$$d(g^{(k+1)}(z)dz) = \nu \wedge (g^{(k)}(z)dz)$$

Let us assume that the first w differentials are not independent

$$\sum_{k \leq w} c_k g^{(k)}(z) dz = 0$$

Then, we find that

$$d\left(\sum_{k \leq w} c_k g^{(k)}(z) dz\right) = \nu \wedge \left(\sum_{k \leq (w-1)} c_k g^{(k)}(z) dz\right) = 0 \implies \sum_{k \leq (w-1)} c_k g^{(k)}(z) dz = 0$$

Thus,

$$\sum_{k \leq (w-1)} c_k g^{(k)}(z) dz \neq 0 \implies \sum_{k \leq w} c_k g^{(k)}(z) dz \neq 0$$

and since $c_0 g^{(0)}(z) dz \neq 0$, all the differentials are independent by induction.

Fay relation for differentials (Kronecker to Decomposition)

$$F(z_1, \alpha_1)F(z_2, \alpha_2) = F(z_1, \alpha_1 + \alpha_2)F(z_2 - z_1, \alpha_2) + F(z_2, \alpha_1 + \alpha_2)F(z_1 - z_2, \alpha_1)$$

↓ decompose ↓

$$\begin{aligned} & \frac{1}{\alpha_1 \alpha_2} \left(\sum_{n=0}^{\infty} g^{(n)}(z_1) \alpha_1^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_2) \alpha_2^n \right) = \\ & \frac{1}{(\alpha_1 + \alpha_2) \alpha_2} \left(\sum_{n=0}^{\infty} g^{(n)}(z_1) (\alpha_1 + \alpha_2)^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_2 - z_1) \alpha_2^n \right) + \\ & \frac{1}{(\alpha_1 + \alpha_2) \alpha_1} \left(\sum_{n=0}^{\infty} g^{(n)}(z_2) (\alpha_1 + \alpha_2)^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_1 - z_2) \alpha_1^n \right) \end{aligned}$$

Fay relation for differentials (decomposition to power matching)

$$\begin{aligned}
 & (\alpha_1 + \alpha_2) \left(\sum_{n=0}^{\infty} g^{(n)}(z_1) \alpha_1^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_2) \alpha_2^n \right) = \\
 & \alpha_1 \left(\sum_{n=0}^{\infty} g^{(n)}(z_1) (\alpha_1 + \alpha_2)^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_2 - z_1) \alpha_2^n \right) + \\
 & \alpha_2 \left(\sum_{n=0}^{\infty} g^{(n)}(z_2) (\alpha_1 + \alpha_2)^n \right) \left(\sum_{n=0}^{\infty} g^{(n)}(z_1 - z_2) \alpha_1^n \right)
 \end{aligned}$$

↓ match coefficients of $\alpha_1^m \alpha_2^n$ ↓

$$\begin{aligned}
 g^{(m-1)}(z_1) g^{(n)}(z_2) + g^{(m)}(z_1) g^{(n-1)}(z_2) = & \sum_{r=0}^n \binom{m-1+r}{r} g^{(m-1+r)}(z_1) g^{(n-r)}(z_2 - z_1) + \\
 & \sum_{r=0}^m \binom{n-1+r}{r} g^{(n-1+r)}(z_2) g^{(m-r)}(z_1 - z_2)
 \end{aligned}$$

Fay relation for differentials (power matching to final form)

$$g^{(m-1)}(z_1)g^{(n)}(z_2) + g^{(m)}(z_1)g^{(n-1)}(z_2) = \sum_{r=0}^n \binom{m-1+r}{r} g^{(m-1+r)}(z_1)g^{(n-r)}(z_2 - z_1) +$$

$$\sum_{r=0}^m \binom{n-1+r}{r} g^{(n-1+r)}(z_2)g^{(m-r)}(z_1 - z_2)$$

↓????? ↓

$$g^{(m)}(z_1)g^{(n)}(z_2) = (-1)^{n+1}g^{(m+n)}(z_1 - z_2)$$

$$+ \sum_{r=0}^m \binom{m+r-1}{r} g^{(m+r)}(z_1)g^{(n-r)}(z_2 - z_1)$$

$$+ \sum_{r=0}^m \binom{n+r-1}{r} g^{(n+r)}(z_2)g^{(m-r)}(z_1 - z_2)$$

$z_1 = t - x$; $z_2 = t \implies$ repeated t dependence \rightarrow repeated x dependence

Periodicity instead of holomorphicity

Broedel et al. 2015 Section 3.2.3

Elliptic version of Kronecker function

$$\Omega(z, \alpha) = \mathbf{e} \left(\alpha \frac{\Im(z)}{\Im(\tau)} \right) F(z, \alpha)$$

$$\Omega(z + 1, \alpha) = \mathbf{e} \left(\alpha \frac{\Im(z + 1)}{\Im(\tau)} \right) F(z + 1, \alpha) = \Omega(z + 1, \alpha)$$

$$\Omega(z + \tau, \alpha) = \mathbf{e} \left(\alpha \frac{\Im(z + \tau)}{\Im(\tau)} \right) F(z + 1, \alpha) = \mathbf{e}(\alpha) \mathbf{e} \left(\alpha \frac{\Im(z)}{\Im(\tau)} \right) \mathbf{e}(-\alpha) F(z, \alpha) = \Omega(z, \alpha)$$

Similarly, we find

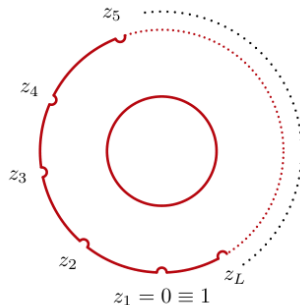
$$\alpha \Omega(z, \alpha) = \sum_{n=0}^{\infty} f^{(n)}(z) dz \alpha^n$$

for perfectly elliptic, but non-holomorphic f .

Application of properties

Properties of differentials:

- Periodic or quasi-periodic, with particular τ
→ faithful to compact Riemann surface
- Integrability and independence
→ suitable for homotopy-invariant integrals
- Constant ($g^{(0)}$) and simple pole ($g^{(1)}$)
→ constructing elliptic polylogarithms
- Fay relation
→ rearranging dependence for integral evaluation

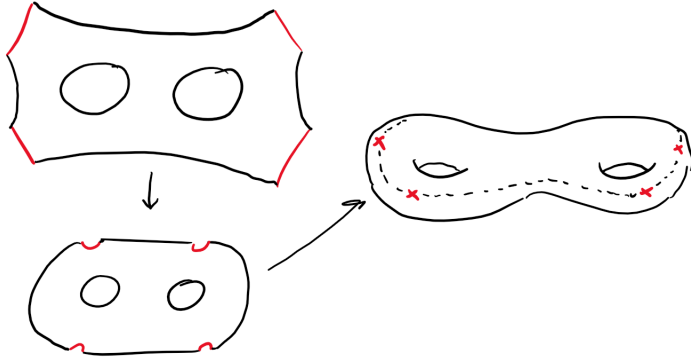


Annulus from open string
Broedel and Kaderli 2022

Outline

1. Abel's map
2. Theta functions
3. Kronecker function
4. Striving for higher genus

Why we care about higher genus



Sketch of analogous construction for genus 2

Questions gathered so far

What about higher genus?

- How do we represent the fundamental domain?
- What choice of differentials can we make?
- What consequences does this have for Abel's map?
- What does the Theta function look like at higher genus?
- Which of the zeros located by odd characteristics are actually reached by Abel's map on compact Riemann surfaces of higher genus?
- Are there similar Jacobi formulas for higher genus theta functions?
- How can we define the Kronecker function at higher genus?
- What does the Fay identity look like at higher genus when theta functions are more complicated?

Questions gathered so far

What about higher genus?

- ✓ How do we represent the fundamental domain?
- ✓ What choice of differentials can we make?
- ✓ What consequences does this have for Abel's map?
- What does the Theta function look like at higher genus?
- Which of the zeros located by odd characteristics are actually reached by Abel's map on compact Riemann surfaces of higher genus?
- Are there similar Jacobi formulas for higher genus theta functions?
- ~ How can we define the Kronecker function at higher genus?
- What does the Fay identity look like at higher genus when theta functions are more complicated?

Schottky group

Bobenko and Klein 2011 and Chan 2022

Schottky group

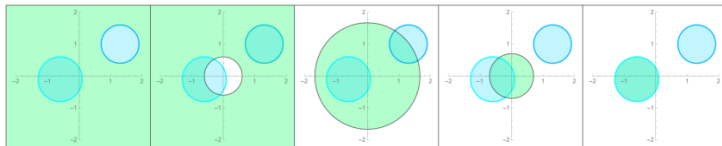
Choosing mutually disjoint discs $\{D_i, D'_i\}$ with interiors $\{\mathring{D}_i, \mathring{D}'_i\}$ on a Riemann sphere, we can choose mobius transformations γ_i such that the exterior of D_i is mapped to the interior of D'_i

$$\gamma_i \in \mathrm{PSL}_2(\mathbb{C}), \quad \gamma_i : z \mapsto \frac{az + b}{cz + d}$$

$$\gamma_i(\bar{C} \setminus \mathring{D}_i) = D'_i$$

$$\gamma_i(\partial D_i) = \partial D'_i$$

The transformations formed by composition of γ_i form a group called a **Schottky group**, usually denoted as Γ .



Möbius transformations mapping outside of one disc to inside of another

Chan 2022

Schottky cover

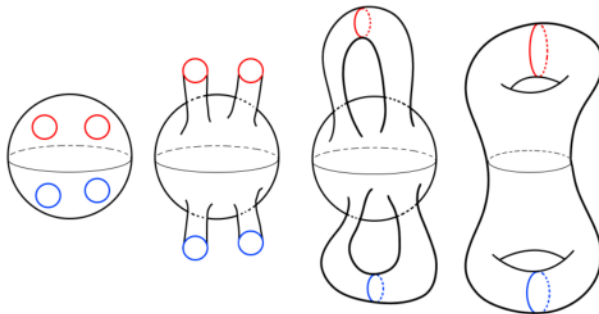
Bobenko and Klein 2011 and Chan 2022

Schottky cover

Given a Schottky group Γ with associated discs $\{D_i, D'_i\}_{i=1}^g$ we can define

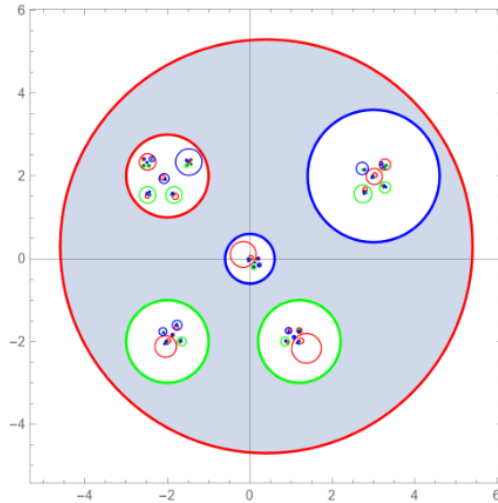
$$F := \bar{\mathbb{C}} \setminus \bigcup_i (\overset{\circ}{D}_i \cup \overset{\circ}{D}'_i) \quad ; \quad \Omega := \bigcup_{\gamma \in \Gamma} \gamma(F)$$

Then, $\mathcal{M} := \Omega/\Gamma$ is a Riemann surface of genus g with fundamental domain F .



Schottky cover

Chan 2022



Schottky cover visual for verbal explanation

Chan 2022

Differentials and Abel's map

Bobenko and Klein 2011 and Chan 2022

We can define cosets of Γ

$$\Gamma/\Gamma_i = \{\gamma_{j_1}^{n_1} \cdots \gamma_{j_k}^{n_k} : \gamma_{j_k} \neq \gamma_i\}$$

$$\Gamma_i \setminus \Gamma = \{\gamma_{j_1}^{n_1} \cdots \gamma_{j_k}^{n_k} : \gamma_{j_1} \neq \gamma_i\}$$

And use these to define holomorphic differentials using fixed points P_i

$$\omega_i = \sum_{\gamma \in \Gamma/\Gamma_i} \left(\frac{1}{z - \gamma(P'_i)} - \frac{1}{z - \gamma(P_i)} \right) = \sum_{\gamma \in \Gamma_i \setminus \Gamma} \left(\frac{1}{\gamma(z) - P'_i} - \frac{1}{\gamma(z) - P_i} \right)$$

Which can then be used to define Abel's map

$$u_i[p] = \int_{p_0}^p \omega_i = \frac{1}{2\pi i} \sum_{\gamma \in \Gamma/\Gamma_i} \ln\{p, \gamma(P'_i), p_0, \gamma(P)\}$$

where

$$\{a, b, c, d\} = \frac{(a-b)(c-d)}{(a-d)(c-b)}$$

Attempt at a Kronecker function

Chan 2022

Focusing on three of the conditions:

1. Generalized Kronecker function should be quasi-periodic
2. Generalized Kronecker function should reduce to aforementioned genus 1 form
3. Generalized Kronecker function should satisfy integrability in a particular way

$$K(z, \{w_1, \dots, w_g\} | \Gamma) = \sum_{\gamma \in \Gamma} \frac{\gamma'(z)}{\gamma(z) - 1} w_1^{\text{ord}_1 \gamma} \dots w_g^{\text{ord}_g \gamma}$$

At Genus 1, for $\gamma : z \mapsto \mathbf{e}(\tau)z = qz$

$$K(z, w | \Gamma) = \sum_{n \in \mathbb{Z}} \frac{q^n}{q^n z - 1} w^n = \dots = \frac{1}{z} \left[1 - \frac{1}{1-z} - \frac{1}{1-w} - \sum_{m, n > 0} q^{mn} (z^m w^n - z^{-m} w^{-n}) \right]$$

Recall

$$F(\xi, \alpha) = -2\pi i \left(\frac{z}{1-z} + \frac{1}{1-w} + \sum_{m, n > 0} (z^m w^n - z^{-m} w^{-n}) q^{mn} \right), \quad \begin{pmatrix} z \\ w \\ q \end{pmatrix} = \mathbf{e} \begin{pmatrix} z \\ \alpha \\ \tau \end{pmatrix}$$

Open questions

Obtaining the Kronecker function in terms of theta functions

- Choice of characters, description of theta's behavior
- Existing attempts inspiring representation with theta functions








More detail in Schottky cover description

- Matching Schottky fundamental domain with usual fundamental polygon
- Alternative choices for generalized Kronecker function

Connection to algebraic curves

- Mapping to other language of describing Riemann surfaces

References

-  Bertola, Marco (2006). *Riemann Surfaces and Theta Functions*.
-  Bobenko, Alexander I. and Christian Klein (2011). *Computational Approach to Riemann Surfaces*. Lecture Notes in Mathematics. Springer Berlin Heidelberg.
-  Broedel, Johannes and Andre Kaderli (2022). “Amplitude recursions with an extra marked point”. In: *Communications in Number Theory and Physics*.
-  Broedel, Johannes et al. (2015). “Elliptic multiple zeta values and one-loop superstring amplitudes”. In: *Journal of High Energy Physics*.
-  Brown, Francis C. S. and Andrey Levin (2013). *Multiple Elliptic Polylogarithms*.
-  Chan, Zhi Cong (2022). “Towards a Higher-Genus Generalization of the Kronecker Function Using Schottky Covers”.
-  Matthes, Nils (2019). “An algebraic characterization of the Kronecker function”. In: *Research in the Mathematical Sciences* 6.3, p. 24. ISSN: 2197-9847.