

WeilRep

Brandon Williams

May 3, 2024

Abstract

weilrep is a Sage program for working with Weil representations and their modular forms and Jacobi forms. In particular it computes Fourier expansions of (bases of) vector-valued modular forms and Jacobi forms. It also computes additive theta lifts and Borchers products, and offers some features for vector-valued quasimodular forms, mock modular forms and harmonic weak Maass forms. This note gives a short explanation of what *weilrep* calculates and several examples of how to use it.

Contents

1	Weil representations	4
1.1	Introduction	4
1.2	Construction	5
1.3	Basic attributes	5
1.3.1	Gram matrix	5
1.3.2	Quadratic form	5
1.3.3	Signature	5
1.3.4	Discriminant	5
1.3.5	Symmetric weights	5
1.3.6	Discriminant group	6
1.3.7	Dual	6
1.3.8	Rescaling	6
1.3.9	Matrix representation	6
1.4	Construction of modular forms	6
1.4.1	Eisenstein series	7
1.4.2	Old Eisenstein series	7
1.4.3	New Eisenstein series	8
1.4.4	Theta series	8
1.4.5	Poincaré series	9
1.4.6	Bruinier–Bundschuh isomorphism	10
1.4.7	Poincaré square series	11
1.4.8	Indefinite theta functions	11
1.4.9	Mock modular forms	11
1.5	Bases of modular forms	11
1.5.1	Modular forms	11
1.5.2	Cusp forms	12
1.5.3	Modular forms with specified order at ∞	13
1.5.4	Nearly holomorphic modular forms	13
1.5.5	Borchers obstruction space	14
1.5.6	Bases of quasimodular forms	14
1.6	Dimension formulas	14

1.6.1	Modular forms	14
1.6.2	Cusp forms	14
1.6.3	Hilbert series	15
2	Vector-valued modular forms	15
2.1	Fourier coefficients	15
2.1.1	Fourier expansion	15
2.1.2	Coefficients	15
2.1.3	Coefficient vector	16
2.1.4	Components	16
2.2	Arithmetic operations	16
2.2.1	Multiplication	16
2.3	Other methods	17
2.3.1	Bol operator	17
2.3.2	Conjugation	17
2.3.3	Derivative and Serre derivative	17
2.3.4	Development coefficients	18
2.3.5	Hecke operators	18
2.3.6	Lattice reduction	19
2.3.7	Linear relations	19
2.3.8	Maass operators	19
2.3.9	Principal part	19
2.3.10	Rankin–Cohen brackets	19
2.3.11	Theta contraction	20
2.3.12	Trace map	20
2.4	Operations on lists of modular forms	21
2.4.1	Coordinates	21
2.4.2	Principal parts	21
2.4.3	Theta contraction	21
2.5	Automorphisms	21
2.5.1	Automorphism group	21
2.5.2	Invariant modular forms	22
2.6	Quasimodular forms	23
2.6.1	Completion	23
2.6.2	Other operations	24
2.7	Mock modular forms	24
2.7.1	Zagier Eisenstein series	25
2.7.2	Maass Eisenstein series	25
2.7.3	Maass Poincaré series	27
2.8	Visualization	28
3	Jacobi forms	30
3.1	Basic attributes	31
3.1.1	Index	31
3.1.2	Weil representation	31
3.2	Construction of Jacobi forms	31
3.2.1	Jacobi Eisenstein series	31
3.2.2	Theta blocks	32
3.2.3	Theta blocks associated to root systems	32
3.2.4	Jacobi Poincaré series	33
3.2.5	Jacobi forms from vector-valued modular forms	33
3.3	Spaces of Jacobi forms	33

3.3.1	Jacobi forms	33
3.3.2	Cusp forms	34
3.3.3	Weak Jacobi forms	34
3.4	Jacobi forms on congruence subgroups	35
3.4.1	Jacobi forms on congruence subgroups	35
3.4.2	Spaces of Jacobi forms	35
3.4.3	Jacobi theta functions	35
3.5	Operations on Jacobi forms	36
3.5.1	Arithmetic operations	36
3.5.2	Development coefficients	36
3.5.3	Direct product	36
3.5.4	Hecke operators	37
3.5.5	is_cusp_form, is_holomorphic	37
3.5.6	Linear relations	38
3.5.7	Pullback	38
3.5.8	Theta decomposition	38
3.5.9	Zero-values	38
3.6	Recovering Fourier coefficients from Jacobi forms	39
4	Modular forms on orthogonal groups	39
4.1	Construction of modular forms	40
4.1.1	Eisenstein series	40
4.1.2	Additive theta lift	40
4.1.3	Borcherds lift	41
4.1.4	Gritsenko lift	41
4.1.5	Spezielschar	42
4.2	Representations of modular forms	42
4.2.1	Fourier expansion	42
4.2.2	Fourier–Jacobi expansion	42
4.2.3	Coefficient dictionary	42
4.3	Inputs for Borcherds products	42
4.3.1	Finding all holomorphic products of a given weight	43
4.3.2	Bases of holomorphic products	43
4.4	Other methods	43
4.4.1	Jacobian	43
4.4.2	Linear relations	44
4.4.3	Maass relations	44
4.4.4	Siegel Phi operator	44
4.4.5	Witt operator	44
5	Modular forms on orthogonal groups II	45
5.1	Construction of modular forms	45
5.1.1	Eisenstein series	45
5.1.2	Additive theta lifts	45
5.1.3	Borcherds lift	46
5.2	Other functions	46
5.3	Special modular forms	46
5.3.1	Hilbert modular forms	46
5.3.2	Siegel modular forms and Paramodular forms	47
5.3.3	Hermitian modular forms	47

6	Algebraic modular forms	48
6.1	Construction	48
6.2	Algebraic modular forms	48
6.2.1	Basis	49
6.2.2	Dimension	49
6.2.3	Eisenstein series	49
6.3	Hecke operators	49
6.3.1	Construction	50
6.3.2	Action	50
6.4	Eigenforms	50
6.4.1	Field	51
6.4.2	Eigenvalue	51
7	Modular forms on complex balls	51
7.1	Weil representations associated to Hermitian lattices	51
7.1.1	Gram matrix	52
7.1.2	Reflections	52
7.2	Borcherds products on unitary groups	53
8	Paramodular forms	53
8.1	Introduction	53
8.2	Construction	54
8.2.1	Eisenstein series	54
8.2.2	Maass space	54
8.3	Hecke operators	54
9	Hermitian modular forms	54
9.1	Introduction	54
9.2	Construction	55
9.2.1	Eisenstein series	55
9.2.2	Maass space	55
9.3	Hecke operators	56
9.3.1	Hecke operators	56
9.3.2	Eigenforms	56
9.3.3	Eigenvalues and L -functions	57

1 Weil representations

1.1 Introduction

An even lattice (L, Q) consists of a free \mathbb{Z} -module L and a nondegenerate \mathbb{Z} -valued quadratic form $Q : L \rightarrow \mathbb{Z}$; that is,

$$\langle x, y \rangle := Q(x + y) - Q(x) - Q(y), \quad x, y \in L$$

defines a nondegenerate symmetric bilinear form. By the polarization identity,

$$Q(x) = \langle x, x \rangle / 2.$$

The class *WeilRep* represents the **dual Weil representation** attached to an even lattice (Λ, Q) , i.e. the representation ρ of $\text{Mp}_2(\mathbb{Z})$ defined on the standard generators $S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ and $T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ by

$$\rho(T)\mathfrak{e}_\gamma = \mathfrak{e}(-Q(\gamma))\mathfrak{e}_\gamma$$

and

$$\rho(S)\mathbf{e}_\gamma = \frac{1}{\sqrt{|\Lambda'/\Lambda|}} \mathbf{e}(\text{sig}(\Lambda)/8) \sum_{\beta \in \Lambda'/\Lambda} \mathbf{e}(\langle \gamma, \beta \rangle) \mathbf{e}_\beta.$$

Here $\mathbf{e}(x) = e^{2\pi i x}$; and \mathbf{e}_γ is the standard basis of $\mathbb{C}[\Lambda'/\Lambda]$; and $\langle \gamma, \beta \rangle := Q(\gamma + \beta) - Q(\gamma) - Q(\beta)$.

1.2 Construction

A *WeilRep* instance is constructed with

`WeilRep(S)`

where S denotes either (1) a Gram matrix; i.e. a symmetric integer matrix whose diagonal consists of even integers; or (2) a QuadraticForm defined over the integers.

1.3 Basic attributes

Let

`w = WeilRep(S)`

be a Weil representation. The following basic attributes can be computed.

1.3.1 Gram matrix

The underlying Gram matrix can be recovered with

`S = w.gram_matrix()`

1.3.2 Quadratic form

The underlying quadratic form can be recovered with

`Q = w.quadratic_form()`

1.3.3 Signature

The signature of the underlying discriminant form can be recovered with

`w.signature()`

This is an element of $\mathbb{Z}/8\mathbb{Z}$ (equal to the signature of the Gram matrix S modulo 8).

1.3.4 Discriminant

The discriminant $|\det(S)|$ is computed with

`w.discriminant()`

1.3.5 Symmetric weights

Call a weight $k \in \frac{1}{2}\mathbb{Z}$ *symmetric* for the Weil representation attached to S if $2k + \text{sig}(S) \equiv 0 \pmod{4}$. In other words, every modular form of weight k is symmetric. (Similarly, call weights k *antisymmetric* if $2k + \text{sig}(S) \equiv 2 \pmod{4}$.) The method

`w.is_symmetric_weight(k)`

outputs 1 if k is a symmetric weight; 0 if k is an antisymmetric weight; and None otherwise.

1.3.6 Discriminant group

The method

`w.ds()`

outputs a set of representatives of the discriminant group $S^{-1}\mathbb{Z}^N/\mathbb{Z}^N$ as a list of vectors.

1.3.7 Dual

The method

`w.dual()`

returns the unitary dual of this representation. (This is the Weil representation attached to the matrix $-S$.)

1.3.8 Rescaling

Let $N \in \mathbb{Z}$, $N \neq 0$. If w is the WeilRep associated to the even lattice $L = (L, Q)$ then $w(N)$ returns the WeilRep associated to the even lattice

$$L(N) = (L, N \cdot Q).$$

In particular $w(-1)$ is the dual of w .

1.3.9 Matrix representation

Let $M \in \mathrm{SL}_2(\mathbb{Z})$. Suppose w is the WeilRep associated to a discriminant form $A = (A, Q)$ and

$$\rho : \mathrm{Mp}_2(\mathbb{Z}) \rightarrow \mathrm{GL} \mathbb{C}[A]$$

is the corresponding Weil representation. Calling

`w(M)`

computes the matrix $\rho(\tilde{M})$ over \mathbb{C} i.e. *numerically* with respect to the canonical basis $\{\mathfrak{e}_\gamma : \gamma \in A\}$ in the ordering determined by `w.ds()`. Here $\tilde{M} = (M, \phi) \in \mathrm{Mp}_2(\mathbb{Z})$ is the preimage whose branch ϕ of the square root of $j(M; \tau)$ satisfies

$$\mathrm{Re}[\phi(\tau)] > 0 \text{ for all } \tau \in \mathbb{H}.$$

Note that if w has odd rank then this is not multiplicative: $w(MN) \neq w(M)w(N)$ in general.

1.4 Construction of modular forms

A *modular form* of weight $k \in \frac{1}{2}\mathbb{Z}$ for the Weil representation ρ attached to a discriminant form (A, Q) is a holomorphic function

$$f : \mathbb{H} \longrightarrow \mathbb{C}[A]$$

that satisfies

$$f(M \cdot \tau) = (c\tau + d)^k \rho(M) f(\tau), \quad (M, (c\tau + d)^{1/2}) \in \mathrm{Mp}_2(\mathbb{Z}), \quad \tau \in \mathbb{H}$$

and which is bounded in the limit $\lim_{y \rightarrow \infty} f(x + iy)$ for every x .

Suppose w is a WeilRep instance. Modular forms for w can be constructed in the following ways.

1.4.1 Eisenstein series

`w.eisenstein_series(k, prec, allow_small_weight = False)`

This returns the Eisenstein series

$$E_{k,0} = \sum_{M \in \Gamma_\infty \backslash \Gamma} \mathfrak{e}_0 \Big|_{k,\rho} M$$

for the dual Weil representation associated to the Gram matrix S with Fourier expansion up to precision $prec$. Here $\Gamma = \text{Mp}_2(\mathbb{Z})$ and Γ_∞ is the subgroup generated by $T = \left(\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, 1\right)$ and $Z = \left(\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}, i\right)$. It only accepts weight $k \geq 1$. Warning: if $k = 3/2$ or $k = 2$ then the result may be a mock modular form or quasimodular form respectively!

The formula for the Fourier coefficients is essentially that given by Bruinier and Kuss [9]. We compute the local L -functions using Cowan–Katz–White’s formula [10] for the Igusa zeta functions attached to quadratic functions (in other words, the local densities); this has the advantage that one does not even need to compute the full Jordan decomposition of the quadratic form.

Example. The Eisenstein series of weight three for the Weil representation attached to the lattice with Gram matrix $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$. Input:

```
w = WeilRep(matrix([[2,1],[1,2]]))
print(w.eisenstein_series(3,5))
```

Output:

```
[(0, 0), 1 + 72*q + 270*q^2 + 720*q^3 + 936*q^4 + 0(q^5)]
[(2/3, 2/3), 27*q^(2/3) + 216*q^(5/3) + 459*q^(8/3) + 1080*q^(11/3) + 1350*q^(14/3) + 0(q^5)]
[(1/3, 1/3), 27*q^(2/3) + 216*q^(5/3) + 459*q^(8/3) + 1080*q^(11/3) + 1350*q^(14/3) + 0(q^5)]
```

1.4.2 Old Eisenstein series

Certain oldform Eisenstein series can be computed using

`w.eisenstein_oldform(k, b, prec)`

Here b should be a nonzero isotropic vector in the discriminant group of w . This returns the oldform Eisenstein series

$$\sum_{\lambda \in \mathbb{Z}/d_b \mathbb{Z}} E_{k,\lambda b},$$

where d_b is the denominator of b (i.e. minimal with $d_b b \in \mathbb{Z}^N$), and

$$E_{k,b} = \sum_{M \in \Gamma_\infty \backslash \Gamma} \mathfrak{e}_b \Big|_k M.$$

Example. The old Eisenstein series of weight $7/2$ for the lattice with Gram matrix (8). Input:

```
w = WeilRep(matrix([[8]]))
w.eisenstein_oldform(7/2, vector([1/2]), 5)
```

Output:

```
[(0, 1 + 126*q + 756*q^2 + 2072*q^3 + 4158*q^4 + 0(q^5)]
[(1/8), 0(q^5)]
[(1/4), 56*q^(3/4) + 576*q^(7/4) + 1512*q^(11/4) + 4032*q^(15/4) + 5544*q^(19/4) + 0(q^5)]
[(3/8), 0(q^5)]
[(1/2), 1 + 126*q + 756*q^2 + 2072*q^3 + 4158*q^4 + 0(q^5)]
[(5/8), 0(q^5)]
[(3/4), 56*q^(3/4) + 576*q^(7/4) + 1512*q^(11/4) + 4032*q^(15/4) + 5544*q^(19/4) + 0(q^5)]
[(7/8), 0(q^5)]
```

1.4.3 New Eisenstein series

Warning: this is experimental (and not at all optimized).

Certain newform Eisenstein series can be computed using

```
w.eisenstein_newform(k, b, prec)
```

Here b should be a nonzero isotropic vector in the discriminant group of w . This returns the newform Eisenstein series

$$\sum_{\lambda \in \mathbb{Z}/d_b\mathbb{Z}} \sum_{\chi} \chi(\lambda) E_{k, \lambda b},$$

where d_b is the denominator of b , and where χ runs through all primitive Dirichlet characters modulo d_b . For fixed χ we use the coefficient formula of [23] to compute the Fourier coefficients of $\sum_{\lambda} \chi(\lambda) E_{k, \lambda b}$ **numerically**; then the sum over all primitive χ is rational and we compute it as such by guessing denominators and rounding. (The denominator we guess is usually far too large.)

Example. Compute the Eisenstein series of weight $5/2$ attached to the Gram matrix ((18)) using

```
w = WeilRep(matrix([[18]]))
w.eisenstein_newform(5/2, vector([1/3]), 5)
```

Via the theta decomposition the output corresponds to the Jacobi Eisenstein series of weight 3 and index 9.

The individual Eisenstein series $E_{k,b}$ can also be approximated as Poincaré series (of index 0), see section 1.5.

1.4.4 Theta series

Note that theta series here come from *negative-definite* Gram matrices because we use the dual Weil representation. This convention is generally more natural in the context of Jacobi forms but in this case rather unfortunate.

This method simply takes the output of PARI's `qfminim()` and writes it as a vector-valued theta function. If w is a `WeilRep` instance that comes from a *negative-definite* Gram matrix or quadratic form then one can construct theta series using

```
w.theta_series(prec, P = None, test_P = True)
```

The required parameter is the precision *prec*. If P is given then it should be a polynomial over \mathbb{Q} in the appropriate number of variables which is homogeneous. *Note:* if P is not *harmonic* with respect to the quadratic form underlying w then the theta series is a quasimodular form; see section 2.6.

Example. The theta series associated to the quadratic form $Q(x, y) = x^2 + y^2$:

$$\Theta(\tau) = \sum_{a, b \in \frac{1}{2}\mathbb{Z}} q^{a^2+b^2} \mathbf{e}_{a,b}.$$

```
w = WeilRep(diagonal_matrix([-2, -2]))
w.theta_series(5)
```

Output:

```
[(0, 0), 1 + 4*q + 4*q^2 + 4*q^4 + 0(q^5)]
[(1/2, 0), 2*q^(1/4) + 4*q^(5/4) + 2*q^(9/4) + 4*q^(13/4) + 4*q^(17/4) + 0(q^(21/4))]
[(0, 1/2), 2*q^(1/4) + 4*q^(5/4) + 2*q^(9/4) + 4*q^(13/4) + 4*q^(17/4) + 0(q^(21/4))]
[(1/2, 1/2), 4*q^(1/2) + 8*q^(5/2) + 4*q^(9/2) + 0(q^(11/2))]
```


The theta series associated to the polynomial $P(x) = x^2$:

$$\Theta(\tau; P) = \sum_{a,b \in \frac{1}{2}\mathbb{Z}} a^2 q^{a^2+b^2} \mathbf{e}_{a,b}.$$

```
R.<x, y> = PolynomialRing(QQ)
w = WeilRep(diagonal_matrix([-2, -2]))
w.theta_series(5, P = x^2)
```

Output:

```
[(0, 0), 2*q + 4*q^2 + 8*q^4 + 0(q^5)]
[(1/2, 0), 1/2*q^(1/4) + q^(5/4) + 9/2*q^(9/4) + 9*q^(13/4) + q^(17/4) + 0(q^(21/4))]
[(0, 1/2), 4*q^(5/4) + 4*q^(13/4) + 16*q^(17/4) + 0(q^(21/4))]
[(1/2, 1/2), q^(1/2) + 10*q^(5/2) + 9*q^(9/2) + 0(q^(11/2))]
```

1.4.5 Poincaré series

Let (A, Q) be a discriminant form of signature $\sigma \in \mathbb{Z}/8\mathbb{Z}$, and let $k \geq 5/2$ be a weight with $\kappa := k - \sigma/2 \in \mathbb{Z}$. The Poincaré series of weight $k \geq 5/2$ and index (β, m) where $\beta \in A$ and $m \in \mathbb{Z} - Q(\beta)$ is the series

$$P_{k,m,\beta}(\tau) = \sum_{M \in \Gamma_\infty \setminus \Gamma} \left(q^m \frac{\mathbf{e}_\beta + (-1)^\kappa \mathbf{e}_{-\beta}}{2} \right) \Big|_{k,\rho^*} M.$$

These series have real but generally irrational Fourier coefficients, given by the following formula (cf. [7])

$$P_{k,m,\beta}(\tau) = \frac{q^m}{2} (\mathbf{e}_\beta + (-1)^\kappa \mathbf{e}_{-\beta}) + \sum_{n,\gamma} c(n, \gamma) q^n \mathbf{e}_\gamma,$$

where: if $m > 0$, then

$$c(n, \gamma) = 2\pi(m/n)^{(1-k)/2} \sum_{c=1}^{\infty} c^{-1} J_{k-1}(4\pi\sqrt{mn}/c) \operatorname{Re} \left[e^{-\pi i k/2} K_c(\beta, m, \gamma, n) \right];$$

if $m < 0$, then

$$c(n, \gamma) = 2\pi(|m|/n)^{(1-k)/2} \sum_{c=1}^{\infty} c^{-1} I_{k-1}(4\pi\sqrt{|m|n}/c) \operatorname{Re} \left[e^{-\pi i k/2} K_c(\beta, m, \gamma, n) \right];$$

and if $m = 0$ then $P_{k,m,\beta}$ coincides with an Eisenstein series. Here J_k, I_k denote the Bessel J - and I -functions and $K_c(\beta, m, \gamma, n)$ is the Kloosterman sum

$$K_c(\beta, m, \gamma, n) = \sum_{d \in (\mathbb{Z}/c\mathbb{Z})^\times} e^{2\pi i(ma+nd)/c} \left\langle \rho(M)^{-1} \mathbf{e}_\beta, \mathbf{e}_\gamma \right\rangle,$$

if $M = \left(\begin{pmatrix} a & b \\ c & d \end{pmatrix}, \phi \right) \in \operatorname{Mp}_2(\mathbb{Z})$ is an element of the metaplectic group with bottom row c, d which satisfies

$$\operatorname{Re}[\phi(\tau)] > 0 \text{ for all } \tau \in \mathbb{H}.$$

Note in particular that if m is negative then the result is a “nearly-holomorphic” modular form.

These series can be computed *approximately* with the method

```
w.poincare_series(k, b, m, prec, nterms)
```

Here, k is the weight; b is a rational vector (a representative of β); $m \in \mathbb{Z} - Q(\beta)$; prec is the precision; and $N = \text{nterms}$ denotes the N at which we truncate the above series in the coefficient formula.

Example. We numerically compute the (unique, up to a multiple) cusp form of weight 8 for the Weil representation attached to the Gram matrix $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$ as a Poincaré series. Note that 8 is an ‘antisymmetric weight’ so all Poincaré series associated to the component $\beta = (0, 0)$ vanish. We can obtain a nonzero form of weight 8 using the index $(\beta, m) = ((1/3, 1/3), 2/3)$. After renormalizing, we find:

```
w = WeilRep([[2, 1], [1, 2]])
w.poincare_series(8, vector([1/3, 1/3]), 2/3, 4, nterms = 50) / (-1.58320744005359)
```

Output:

```
[(0, 0), 0(q^4)]
[(2/3, 2/3), 0.000000000000000*q^(-1/3) + 1.000000000000000*q^(2/3) - 15.9999999992044*q^(5/3)
+ 103.999999990887*q^(8/3) - 320.000000336077*q^(11/3) + 0(q^(14/3))]
[(1/3, 1/3), 0.000000000000000*q^(-1/3) - 1.000000000000000*q^(2/3) + 15.9999999992044*q^(5/3)
- 103.999999990887*q^(8/3) + 320.000000336077*q^(11/3) + 0(q^(14/3))]
```

This may be compared with the cusp form computed using exact arithmetic (cf. 1.4.2)

```
w.cusp_forms_basis(8, 4)
```

Output:

```
[(0, 0), 0(q^10)]
[(2/3, 2/3), q^(2/3) - 16*q^(5/3) + 104*q^(8/3) - 320*q^(11/3) + 0(q^(14/3))]
[(1/3, 1/3), -q^(2/3) + 16*q^(5/3) - 104*q^(8/3) + 320*q^(11/3) + 0(q^(14/3))]
```

Of course the series $q^{2/3} - 16q^{5/3} + 104q^{8/3} + 320q^{11/3} \pm \dots$ appearing here is just $\eta^{16}(\tau)$.

1.4.6 Bruinier–Bundschuh isomorphism

Bruinier and Bundschuh [8] gave an isomorphism between the spaces of modular forms for lattices of odd prime discriminant and scalar-valued modular forms of prime level with the quadratic character whose Fourier expansions are supported either entirely on quadratic residues or entirely on quadratic nonresidues.

These lifts can be constructed with the method

```
w.bb_lift(mf)
```

Here mf is a `ModularFormElement` of the appropriate level and character that satisfies the plus/minus-space condition on Fourier coefficients.

Example. To obtain the Eisenstein series of weight three for the Gram matrix $S = \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$. Input:

```
w = WeilRep(matrix([[2, 1], [1, 2]]))
chi = DirichletGroup(3)[1]
mf = ModularForms(chi, 3, prec=20).basis()[0]
w.bb_lift(mf)
```

Output:

```
[(0, 0), 1 + 72*q + 270*q^2 + 720*q^3 + 936*q^4 + 2160*q^5 + 0(q^6)]
[(2/3, 2/3), 27*q^(2/3) + 216*q^(5/3) + 459*q^(8/3) + 1080*q^(11/3) + 1350*q^(14/3) + 2592*q^(17/3) + 0(q^6)]
[(1/3, 1/3), 27*q^(2/3) + 216*q^(5/3) + 459*q^(8/3) + 1080*q^(11/3) + 1350*q^(14/3) + 2592*q^(17/3) + 0(q^6)]
```

1.4.7 Poincaré square series

Let $\beta \in \Lambda'/\Lambda$ and $m \in \mathbb{Z} - Q(\beta)$ be an index and define by $Q_{k,m,\beta}$ the Poincaré square series

$$Q_{k,m,\beta} = \sum_{\lambda \in \mathbb{Z}} P_{k,\lambda^2 m, \lambda \beta}.$$

Here $P_{k,m,\beta}$ denotes the Poincaré series of exponential type (as in [7]). The Fourier coefficients of these series are rational and they can be computed in terms of Eisenstein series (associated to other lattices) [24]. (In fact these are the basic modular forms which are used here to produce cusp forms.) In this code we require $k \geq 5/2$.

These series are implemented with

```
w.pss(k, beta, m, prec)
```

The construction of modular forms of antisymmetric weights is similar [26] and implemented with

```
w.pssd(k, beta, m, prec)
```

1.4.8 Indefinite theta functions

Let L be a lattice of signature $(1, n)$ and fix a cone P of positive norm vectors in $L \otimes \mathbb{R}$. Zagier has defined a family of theta functions associated to L :

$$\Theta_L^{\text{Zw}}(\tau; c_1, c_2) = \sum_{\lambda \in L'} \left[\operatorname{erf} \left(\frac{\langle c_1, \lambda \rangle}{\sqrt{Q(c_1)}} \sqrt{y/\pi} \right) - \operatorname{erf} \left(\frac{\langle c_2, \lambda \rangle}{\sqrt{Q(c_2)}} \sqrt{y/\pi} \right) \right] q^{-Q(\lambda)} \epsilon_{\lambda+L},$$

where $c_1, c_2 \in P$. Here $\operatorname{erf}(x)$ is the Gauss error function

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(t^2) dt.$$

This theta function is not holomorphic but transforms like a modular form of weight $(1+n)/2$ with respect to the dual Weil representation ρ_L^* :

$$\Theta_L^{\text{Zw}}(M \cdot \tau) = \rho_L^*(M) \sqrt{c\tau + d}^{1+n} \Theta_L^{\text{Zw}}(\tau), \quad (M, \sqrt{c\tau + d}) \in \operatorname{Mp}_2(\mathbb{Z}).$$

To obtain modular forms we take $c_1, c_2 \in \partial P$ to be norm-zero vectors lying on the boundary of a common cone and define Zagier's theta function as the radial limit:

$$\Theta_L^{\text{Zw}}(\tau; c_1, c_2) = \lim_{h \rightarrow 0} \Theta_L^{\text{Zw}}(\tau; c_1 + hv, c_2 + hv), \quad v \in P.$$

1.4.9 Mock modular forms

Currently only mock Eisenstein series and mock Poincaré series can be constructed; see section 2.7 for details.

1.5 Bases of modular forms

1.5.1 Modular forms

The method

```
w.modular_forms_basis(k, prec, eta_twist = 0)
```

returns a basis in echelon form of the space of modular forms $M_k(\rho \otimes \chi^N)$ with Fourier expansions to precision $O(q^{prec})$, where χ is the multiplier system of the Dedekind eta function $\eta(\tau) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n)$ and N is the optional parameter *eta_twist* (which is 0 unless specified otherwise).

For symmetric weights at least $5/2$ or antisymmetric weights at least $7/2$ we use linear combinations of Eisenstein series and PSS (cf. 1.3.1, 1.3.7). In weights 0 and $1/2$ we use an algorithm based on Ehlen–Skoruppa’s method for computing Weil invariants [12]. Otherwise we try to reduce the problem to higher weight forms, generally by writing M_k as the intersection

$$M_k(\rho) = E_4(\tau)^{-1} M_{k+4}(\rho) \cap E_6(\tau)^{-1} M_{k+6}(\rho)$$

where E_4, E_6 are the scalar Eisenstein series.

Example. Modular forms of weight $11/2$ for the Weil representation attached to the Cartan matrix A_5 , with Fourier expansions up to $O(q^5)$:

```
WeilRep(CartanMatrix(['A', 5])).modular_forms_basis(11/2, 4)
```

Output:

```
[(0, 0, 0, 0, 0), 1 + 180*q + 4404*q^2 + 26562*q^3 + 0(q^4)]
[(5/6, 2/3, 1/2, 1/3, 1/6), 20*q^(7/12) + 1472*q^(19/12) + 14076*q^(31/12) + 57920*q^(43/12) + 0(q^4)]
[(2/3, 1/3, 0, 2/3, 1/3), q^(1/3) + 693*q^(4/3) + 8680*q^(7/3) + 43252*q^(10/3) + 0(q^4)]
[(1/2, 0, 1/2, 0, 1/2), 552*q^(5/4) + 7040*q^(9/4) + 39888*q^(13/4) + 0(q^4)]
[(1/3, 2/3, 0, 1/3, 2/3), q^(1/3) + 693*q^(4/3) + 8680*q^(7/3) + 43252*q^(10/3) + 0(q^4)]
[(1/6, 1/3, 1/2, 2/3, 5/6), 20*q^(7/12) + 1472*q^(19/12) + 14076*q^(31/12) + 57920*q^(43/12) + 0(q^4)]
-----
[(0, 0, 0, 0, 0), 34*q - 156*q^2 + 162*q^3 + 0(q^4)]
[(5/6, 2/3, 1/2, 1/3, 1/6), -7*q^(7/12) - 13*q^(19/12) + 171*q^(31/12) - 157*q^(43/12) + 0(q^4)]
[(2/3, 1/3, 0, 2/3, 1/3), q^(1/3) + 18*q^(4/3) - 14*q^(7/3) - 380*q^(10/3) + 0(q^4)]
[(1/2, 0, 1/2, 0, 1/2), q^(1/4) - 30*q^(5/4) + 81*q^(9/4) - 12*q^(13/4) + 0(q^4)]
[(1/3, 2/3, 0, 1/3, 2/3), q^(1/3) + 18*q^(4/3) - 14*q^(7/3) - 380*q^(10/3) + 0(q^4)]
[(1/6, 1/3, 1/2, 2/3, 5/6), -7*q^(7/12) - 13*q^(19/12) + 171*q^(31/12) - 157*q^(43/12) + 0(q^4)]
```

We see that this is a two dimensional space. The vector-valued modular forms are separated by a row of dashes.

1.5.2 Cusp forms

The method

```
w.cusp_forms_basis(k, prec, eta_twist = 0)
```

returns a basis in echelon form of the space of cusp forms $S_k(\rho)$ with Fourier expansions to precision $O(q^{prec})$. If the optional parameter $N = \text{eta_twist}$ is given then we instead compute a basis of cusp forms associated to the Weil representation twisted by χ^N where χ is the eta multiplier.

Example. Cusp forms of weight 4 for the Weil representation attached to the Cartan matrix A_6 , with Fourier expansions up to $O(q^4)$:

```
WeilRep(CartanMatrix(['A', 6])).cusp_forms_basis(4, 4)
```

Output:

```
[(0, 0, 0, 0, 0, 0), 0(q^4)]
[(6/7, 5/7, 4/7, 3/7, 2/7, 1/7), -17*q^(4/7) + 68*q^(11/7) - 135*q^(18/7) + 125*q^(25/7) + 0(q^4)]
[(5/7, 3/7, 1/7, 6/7, 4/7, 2/7), 5*q^(2/7) + 27*q^(9/7) - 89*q^(16/7) + 40*q^(23/7) + 0(q^4)]
[(4/7, 1/7, 5/7, 2/7, 6/7, 3/7), q^(1/7) - 45*q^(8/7) + 340*q^(15/7) + 0(q^4)]
[(3/7, 6/7, 2/7, 5/7, 1/7, 4/7), -q^(1/7) + 45*q^(8/7) - 340*q^(15/7) + 0(q^4)]
[(2/7, 4/7, 6/7, 1/7, 3/7, 5/7), -5*q^(2/7) - 27*q^(9/7) + 89*q^(16/7) - 40*q^(23/7) + 0(q^4)]
[(1/7, 2/7, 3/7, 4/7, 5/7, 6/7), 17*q^(4/7) - 68*q^(11/7) + 135*q^(18/7) - 125*q^(25/7) + 0(q^4)]
```

1.5.3 Modular forms with specified order at ∞

The method

```
w.basis_vanishing_to_order(k, N, prec, inclusive=False)
```

returns a basis in echelon form of the space of modular forms of weight k which vanish to order at least N at ∞ . Setting the optional parameter *inclusive* to True forces the coefficient of q^N itself to zero.

Example. Let $M_{13}(\rho^*)$ be the space of modular forms of weight 13 for the Gram matrix $S = \begin{pmatrix} -2 & -1 \\ -1 & -2 \end{pmatrix}$. To compute the subspace of modular forms which vanish to order at least 2/3:

```
WeilRep(matrix([[ -2, -1], [-1, -2]])).basis_vanishing_to_order(13, 2/3, 4)
```

Output:

```
[(0, 0), q - 18*q^2 + 108*q^3 + 0(q^4)]
[(1/3, 1/3), 3*q^(4/3) - 69*q^(7/3) + 690*q^(10/3) + 0(q^4)]
[(2/3, 2/3), 3*q^(4/3) - 69*q^(7/3) + 690*q^(10/3) + 0(q^4)]
```

1.5.4 Nearly holomorphic modular forms

A *nearly-holomorphic modular form* is a function which transforms like a modular form and is holomorphic on \mathbb{H} but may have a pole at cusps. The method

```
w.nearly_holomorphic_modular_forms_basis(k, N, prec, inclusive = False)
```

returns a basis of the space of nearly-holomorphic modular forms of weight k with a pole of order at most N at ∞ with principal parts which are as simple as possible. Setting the optional parameter *inclusive* to False does not allow forms with pole order exactly N .

Example. In [28] Zagier considered a sequence of forms $g_D(\tau) \in M_{3/2}^+(\Gamma_0(4))$ whose Fourier expansions take the form

$$g_D(\tau) = q^{-D} + \sum_{n=0}^{\infty} B(D, n)q^n, \quad B(D, n) \in \mathbb{Z}$$

in his work on traces of singular moduli. We can realize these as modular forms for the Gram matrix (2) and compute them as follows.

```
WeilRep(matrix([[2]])).nearly_holomorphic_modular_forms_basis(3/2, 2, 3)
```

Output:

```
[(0, -2 - 492*q - 7256*q^2 - 53008*q^3 + 0(q^4)]
[(1/2), q^(-1/4) + 248*q^(3/4) + 4119*q^(7/4) + 33512*q^(11/4) + 192513*q^(15/4) + 0(q^4)]
-----
[(0, q^-1 - 2 - 143376*q - 26124256*q^2 - 1417904008*q^3 + 0(q^4)]
[(1/2), -26752*q^(3/4) - 8288256*q^(7/4) - 561346944*q^(11/4) - 18508941312*q^(15/4) + 0(q^4)]
-----
[(0, -565760*q - 190356480*q^2 - 16555069440*q^3 + 0(q^4)]
[(1/2), q^(-5/4) + 85995*q^(3/4) + 52756480*q^(7/4) + 5874905295*q^(11/4) + 292658282496*q^(15/4) + 0(q^4)]
-----
[(0, q^-2 - 18473000*q - 29071392966*q^2 - 8251987131648*q^3 + 0(q^4)]
[(1/2), -1707264*q^(3/4) - 5734772736*q^(7/4) - 2225561184000*q^(11/4) - 312211675238400*q^(15/4) + 0(q^4)]
```

1.5.5 Borchers obstruction space

Define the *Borchers obstruction space* as the space of holomorphic modular forms whose constant terms are multiples of \mathfrak{e}_0 . Following [4] (for lattices of the correct signature) elements of this space may be thought of as obstructions to the existence of Borchers products with specified divisor and weight. In large weight (at least $5/2$) this is spanned by the cusp space $S_k(\rho)$ and the Eisenstein series $E_{k,0}$.

This space can be computed with

```
w.borchers_obstructions(k, prec)
```

where k is the weight and $prec$ is the precision to which the Fourier series are computed.

1.5.6 Bases of quasimodular forms

See section 2.6 for the definition of quasimodular forms and their properties. Given a WeilRep w , a basis of quasimodular forms in echelon form can be constructed using

```
w.quasimodular_forms_basis(k, prec)
```

where k is the weight, and $prec$ is the precision of the Fourier expansions.

1.6 Dimension formulas

We use the Riemann-Roch theorem to compute dimensions of spaces of modular forms in weight at least 2. In small weights we compute a *basis* of $M_k(\rho)$ first and then take its length. (This is slow!)

1.6.1 Modular forms

The method

```
w.modular_forms_dimension(k, eta_twist=0)
```

computes the dimension

$$\dim M_k(\rho \otimes \chi^N),$$

where χ is the multiplier system of $\eta(\tau) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n)$ and N is the optional parameter *eta_twist* (by default $N = 0$).

1.6.2 Cusp forms

The method

```
w.cusp_forms_dimension(k, eta_twist=0)
```

computes the dimension

$$\dim S_k(\rho \otimes \chi^N),$$

where χ is the multiplier system of $\eta(\tau) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n)$ and N is the optional parameter *eta_twist* (by default $N = 0$).

1.6.3 Hilbert series

The *Hilbert series* of the Weil representation ρ for the lattice L is the series

$$\text{Hilb}_\rho(t) := \sum_{k=0}^{\infty} \dim M_{k+\varepsilon}(\rho) t^k,$$

where $\varepsilon = 0$ if L has even rank and $\varepsilon = 1/2$ if L has odd rank. It has the form

$$\text{Hilb}_\rho(t) = \frac{P(t)}{(1-t^4)(1-t^6)}$$

for some polynomial $P(t)$.

The method

```
w.hilbert_series()
```

computes the Hilbert series $\text{Hilb}_\rho(t)$ as a power series.

The method

```
w.hilbert_polynomial()
```

computes the polynomial $P(t)$.

2 Vector-valued modular forms

Vector-valued modular forms are instances of the *WeilRepModularForm* class. Suppose f is a vector-valued modular form.

2.1 Fourier coefficients

2.1.1 Fourier expansion

The Fourier expansion of f is recovered with

```
f.fourier_expansion()
```

The output is a list of tuples of the form $(g, N, \phi_g(q))$ where g is a vector, $N \in \mathbb{Q}$ and ϕ_g is a power series in q , meant to indicate that

$$f = \sum_g q^{-N} \phi_g(q) \mathfrak{e}_g.$$

2.1.2 Coefficients

$f.coefficients()$ produces the Fourier coefficients of f as a dictionary. The keys are tuples (g_1, \dots, g_d, n) and the output is the coefficient of $q^n \mathfrak{e}_{(g_1, \dots, g_d)}$ in f .

Example. Let f be the (vector-valued) Cohen Eisenstein series of weight $5/2$:

$$f(\tau) = (1 - 70q - 120q^2 - 240q^3 - 550q^4 - \dots) \mathfrak{e}_0 + (-10q^{1/4} - 48q^{5/4} - 250q^{9/4} - 240q^{13/4} - 480q^{17/4} - \dots) \mathfrak{e}_{1/2}.$$

Construct it with

```
f = WeilRep([-2]).eisenstein_series(5/2, 5)
```

To extract the coefficient -70 use

```
f.coefficients()[(0, 1)]
```

To extract the coefficient -48 use

```
f.coefficients()[(1/2, 5/4)]
```

2.1.3 Coefficient vector

```
f.coefficient_vector()
```

sorts the Fourier coefficients of f and combines them to a vector.

Example. Let f be the Cohen Eisenstein series from the previous section. The coefficient vector

```
f.coefficient_vector()
```

is

```
(1, -10, -70, -48, -120, -250, -240, -240, -550, -480)
```

The `coefficient_vector` method takes a few optional arguments, most importantly:

- *starting_from*: the exponent at which we begin counting coefficients;
- *ending_with*: the exponent at which we stop counting coefficients.

2.1.4 Components

The method

```
f.components()
```

produces the components of f as a dictionary. The keys are *tuples* (g_1, \dots, g_d) , where (g_1, \dots, g_d) is a vector in the dual lattice, and the output is the Fourier series f_{g_1, \dots, g_d} (i.e. the component in f) as a power series with exponents rounded up to integers.

2.2 Arithmetic operations

Addition and subtraction are defined as usual.

2.2.1 Multiplication

Multiplication of vector-valued modular forms should be understood as the tensor product. If $f \in M_{k_1}(\rho_{S_1})$ and $g \in M_{k_2}(\rho_{S_2})$ are vector-valued modular forms for Weil representations associated to S_1 and S_2 then $f \otimes g$ is a modular form for the direct sum $S_1 \oplus S_2$.

Example. Input:

```
w = WeilRep(matrix([[ -2]]))
E = w.eisenstein_series(5/2, 5)
E * E
```

The output is a modular form of weight 5 for the dual Weil representation attached to $\begin{pmatrix} -2 & 0 \\ 0 & -2 \end{pmatrix}$:

```
[(0, 0), 1 - 140*q + 4660*q^2 + 16320*q^3 + 46900*q^4 + 0(q^5)]
[(1/2, 0), -10*q^(1/4) + 652*q^(5/4) + 4310*q^(9/4) + 25420*q^(13/4) + 63340*q^(17/4) + 0(q^5)]
[(0, 1/2), -10*q^(1/4) + 652*q^(5/4) + 4310*q^(9/4) + 25420*q^(13/4) + 63340*q^(17/4) + 0(q^5)]
[(1/2, 1/2), 100*q^(1/2) + 960*q^(3/2) + 7304*q^(5/2) + 28800*q^(7/2) + 95140*q^(9/2) + 0(q^5)]
```


To multiply $f \in M_\ell(\rho)$ by a scalar-valued modular form g of weight k one should convert g to a vector-valued modular form (for the rank zero lattice) using the command

```
smf(k, g)
```

and then multiply as usual.

Example. To multiply the Cohen Eisenstein series of weight $5/2$ by the discriminant Δ , use

```
E = WeilRep(matrix([[ -2]])).eisenstein_series(5/2, 5)
E * smf(12, delta_qexp(5))
```

2.3 Other methods

2.3.1 Bol operator

If f is a modular form of integral weight $k \leq 1$ then its image under the *Bol operator*

$$D = \left(\frac{1}{2\pi i} \frac{d}{d\tau} \right)^{1-k} f(\tau)$$

is a modular form of weight $2 - k$. This is implemented by the method

```
f.bol()
```

2.3.2 Conjugation

The method

```
f.conjugate(A)
```

can be used to change lattice bases. If f is a modular form for the Gram matrix S then $f.conjugate(A)$ is a modular form for the Gram matrix $A^T S A$. (Note: A does not need to be invertible.)

2.3.3 Derivative and Serre derivative

The derivative of a modular form is generally a *quasimodular form*, not a modular form. This is implemented with the method

```
f.derivative()
```

See section 2.6 for more details.

If f is a modular form of weight k then its *Serre derivative*

$$Sf(\tau) = \frac{1}{2\pi i} f'(\tau) - \frac{k}{12} f(\tau) E_2(\tau)$$

is a modular form of weight $k + 2$. This is implemented by the method

```
f.serre_derivative()
```

2.3.4 Development coefficients

Let (L, Q) be an even lattice and let $K \subseteq L$ be a sublattice with positive-definite orthogonal complement K^\perp . For any vector-valued modular form

$$F(\tau) = \sum_{\gamma \in L'/L} \sum_{n \in \mathbb{Z} - Q(\gamma)} c(n, \gamma) q^n \mathbf{e}_\gamma \in M_k(\rho_L),$$

and any vectors $v_1, \dots, v_N \in K^\perp$, following section 5 of [27] the *development coefficient* $D_{v_1, \dots, v_N}^K F$ is a ρ_K -valued modular form of weight $k + N + \text{rank}(K^\perp)/2$, with Fourier expansion

$$D_{v_1, \dots, v_N}^K F(\tau) = \sum_{\gamma \in K'/K} \sum_{n \in \mathbb{Z} - Q(\gamma)} \sum_{\substack{\lambda \in (K^\perp)' \\ (\gamma, \lambda + K^\perp) \in L'/L}} c(n - Q(\lambda), (\gamma, \lambda + K^\perp)) G_N^{k-1+\text{rank}(K^\perp)/2}(\lambda, nQ/2) q^n \mathbf{e}_\gamma.$$

Here G_N^s denotes a multilinear Gegenbauer or ultraspherical polynomial. For scalar-index Jacobi forms these operators are exactly the development coefficients of Eichler–Zagier [13]. (See also section 3.4 below.)

These operators are implemented by the method

`F.development_coefficient(lattice_basis, v = [])`

Here *lattice_basis* should be a \mathbb{Z} -basis of the sublattice K (given as a list of vectors, which may be the empty list) and *v* should be the list of vectors v_1, \dots, v_N .

2.3.5 Hecke operators

The method

`f.hecke_T(N)`

applies the Hecke operator T_N to f using the formula of [1]. The lattice does not have to be positive-definite. (Warning: this is only implemented when N is coprime to the level of the lattice!)

Similarly the methods

`f.hecke_U(N)`

and

`f.hecke_V(N)`

apply the index-raising Hecke operators U_N and V_N (cf. [5], [22]). These are maps

$$U_N : M_k(\rho) \longrightarrow M_k(\rho(N^2)), \text{ and } V_N : M_k(\rho) \longrightarrow M_k(\rho(N)),$$

where $\rho(N)$ denotes the Weil representation for the lattice $L(N)$ with quadratic form rescaled by N , i.e. $L(N) = (L, N \cdot Q)$. They specialize to the Eichler–Zagier Hecke operators on Jacobi forms when L is positive-definite.

Finally the method

`f.hecke_P(N)`

implements the index-*lowering* Hecke operator P_N of [5]. This is a map

$$P_N : M_k(\rho(N^2)) \longrightarrow M_k(\rho)$$

with the property $P_N \circ U_N = \text{id}$.

2.3.6 Lattice reduction

Suppose L is an isotropic lattice over \mathbb{Z} of signature (b^+, b^-) with a norm zero vector z . The method

`f.reduce_lattice()`

implements the lattice-reduction map from L to the signature $(b^+ - 1, b^- - 1)$ lattice z^\perp/z . In the notation of Borchers ([3], especially sections 5, 6) this takes the form F_M as input and yields the form F_K . The norm-zero vector z can be provided; if no z is given then we try to find one using PARI `qfsolve()`.

In this setup note that $|L| = N^2 \cdot |z^\perp/z|$ for some N . In particular if L is isotropic but has squarefree discriminant (or if L has odd rank, and $|L|/2$ is squarefree) then this method always yields a modular form on a smaller lattice whose discriminant form is equivalent to that of L .

2.3.7 Linear relations

To compute the space of linear relations among vector-valued modular forms f_1, \dots, f_N of the same weight and the same Weil representation, use the method

`relations(f_1, ..., f_N)`

Warning: this uses only the known Fourier coefficients! If f_1, \dots, f_N have weight k and their Fourier expansions are known to precision less than $k/12$ (the Sturm bound) then the result may be incorrect.

2.3.8 Maass operators

The Maass raising and lowering operators are implemented with the methods `f.raising_operator()` and `f.lowering_operator()`, respectively. If f is an almost-holomorphic modular form of weight k then its images under the raising and lowering operators are

$$R_k f = 2i\partial_\tau f + kf/y \quad \text{and} \quad L_k f = -2iy^2\partial_\tau f.$$

In particular if f is holomorphic then $L_k f = 0$.

2.3.9 Principal part

Suppose F is a nearly holomorphic modular form.

`F.principal_part()`

outputs its principal part (its terms with negative exponent, and the \mathfrak{e}_0 -component of its constant term) as a `WeilRepPrincipalPart` instance. This is useful in the Borchers lift as it determines the weight and divisor of the output.

2.3.10 Rankin–Cohen brackets

If f_1 and f_2 are modular forms of weight k_1 and k_2 attached to the Gram matrices \mathbf{S}_1 and \mathbf{S}_2 , and $N \in \mathbb{N}_0$, then we obtain modular forms of weight $k_1 + k_2 + 2N$ as Rankin–Cohen brackets:

$$[f_1, f_2]_N = \sum_{r=0}^N (-1)^r \binom{k_1 + N - 1}{N - r} \binom{k_2 + N - 1}{r} \frac{d^r}{d\tau^r} f_1(\tau) \otimes \frac{d^{N-r}}{d\tau^{N-r}} f_2(\tau) \in M_{k_1 + k_2 + 2N}(\mathbf{S}_1 \oplus \mathbf{S}_2).$$

These are cusp forms if $N \geq 1$. The Rankin–Cohen brackets are implemented as the function `rankin_cohen(N, f_1, f_2)`.

Note that certain expressions which are trivial for scalar modular forms are generally nonzero for vector-valued forms. For example, if f has weight k then its first Rankin–Cohen bracket with itself,

$$[f, f]_1 = k(f \otimes f' - f' \otimes f)$$

is generally nonzero.

Example. The first Rankin–Cohen bracket of the standard unary theta function with itself is nonzero. Compute it with

```
w = WeilRep(matrix([[2]]))
theta = w.theta_series(10)
rankin_cohen(1, theta, theta)
```

When $N = 0$ the Rankin–Cohen bracket reduces to the (tensor) product of two modular forms.

2.3.11 Theta contraction

Suppose f is a modular form of weight k for a Gram matrix \tilde{S} which can be written as a block matrix

$$\tilde{S} = \begin{pmatrix} S & S\beta \\ (S\beta)^T & 2m + \beta^T S\beta \end{pmatrix}$$

where $m \in \mathbb{Q}$, $m > 0$. The *theta contraction* Θf of f is a twisted product of f with a rank one theta function. The result is a modular form of weight $k + 1/2$ for the Gram matrix S . This is useful in the context of theta lifts as it corresponds to the pullbacks of modular forms on orthogonal groups.

Example. Compute the theta contraction of the weight three Eisenstein series E attached to the Gram matrix $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$. Input:

```
S = matrix([[2, 1], [1, 2]])
E = WeilRep(S).eisenstein_series(3,5)
print(E.theta_contraction())
```

Output:

```
[(0), 1 + 126*q + 756*q^2 + 2072*q^3 + 4158*q^4 + 0(q^5)]
[(1/2), 56*q^(3/4) + 576*q^(7/4) + 1512*q^(11/4) + 4032*q^(15/4) + 5544*q^(19/4) + 0(q^5)]
```

i.e. ΘE is the Eisenstein series of weight $7/2$ attached to the Gram matrix (2).

2.3.12 Trace map

Suppose $f \in M_k(\rho)$ and $g \in M_\ell(-\rho)$ are modular forms whose Gram matrices are negatives of one another. The operation

$f \ \& \ g$

computes the trace-map

$$\langle f, g \rangle := \sum_{\gamma} f_{\gamma}(\tau) g_{\gamma}(\tau) \in M_{k+\ell},$$

which is a (scalar) modular form of weight $k + \ell$.

2.4 Operations on lists of modular forms

The output of most functions that yield lists of vector-valued modular forms is actually an instance of the `WeilRepModularFormsBasis` class. In addition to the usual commands that apply to lists, `WeilRepModularFormsBasis` has a few extra methods.

Suppose X is a `WeilRepModularFormsBasis` instance.

2.4.1 Coordinates

Suppose f is a vector-valued modular form for the same lattice and of the same weight as X . Write $X = (x_1, \dots, x_n)$. Then

`X.coordinates(f)`

computes a vector $v = (v_1, \dots, v_n)$ such that

$$f = v_1 x_1 + \dots + v_n x_n$$

(and raises a `ValueError` if this does not exist).

Warning: we only compute v using the known Fourier coefficients. If an insufficient number of coefficients are known then the result is likely to be wrong.

2.4.2 Principal parts

`X.principal_parts()` enumerates the principal parts of all elements of X as a string separated by newlines.

2.4.3 Theta contraction

`X.theta()` computes the theta contraction of all elements of X simultaneously. The result is again a `WeilRepModularFormsBasis` instance.

2.5 Automorphisms

Let $A = (A, Q)$ be a discriminant form. By an *automorphism* of A we mean a \mathbb{Z} -linear map $g : A \rightarrow A$ for which $Q \circ g = Q$. (In other words the group of automorphisms is the orthogonal group $O(A)$.)

2.5.1 Automorphism group

Let

`w = WeilRep(S)`

be a `WeilRep` instance. The automorphism group of w can be constructed with

`G = w.automorphism_group()`

(Warning: this can be slow, particularly if G is reasonably big!)

G acts as a list of *WeilRepAutomorphisms* g . To view G explicitly it is better to type `list(G)`. Each g can be used as follows:

(i) if f is a `WeilRepModularForm`, with Fourier expansion

$$f(\tau) = \sum_{x \in A} f_x(\tau) e_x,$$

then $g(f)$ is the WeilRepModularForm

$$g(f)(\tau) = \sum_{x \in A} f_x(\tau) e_{g \cdot x}.$$

(ii) if $x \in A$ then $g(x) \in A$ is the image of x under g .

Additionally WeilRepAutomorphisms can be multiplied (corresponding to composition) and inverted using the syntax

`~g`

Some additional methods for the WeilRepAutomorphismGroup G are:

- Generators: $G.gens()$. This produces a list of generators of G .
- Character group: $G.characters()$. This produces a list of all the characters, or homomorphisms $\chi : G \rightarrow \mathbb{C}^\times$. Here a character is represented as a list

$$\chi = [\chi_1, \dots, \chi_N],$$

where: if $G = [g_1, \dots, g_N]$ then $\chi_i = \chi(g_i)$.

2.5.2 Invariant modular forms

Let w be a WeilRep instance with automorphism group G , and let $\chi : G \rightarrow \mathbb{C}^\times$ be a character.

The method

`w.invariant_forms_dimension(k, chi = chi)`

computes the dimension

$$\dim M_{k,\chi}(\rho),$$

where $M_{k,\chi}(\rho)$ is the subspace of forms $f \in M_k(\rho)$ for which $g \cdot f = \chi(g)f$ for all $g \in G$. If $k \geq 5/2$ then this is reasonably fast (up to determining G) as we can use the Riemann–Roch formula. If χ is not given then we assume that χ is the trivial character. (Warning: in this case the weight k must satisfy $2k + \sigma(A, Q) \equiv 0 \pmod{4}$.)

Note: if G is not abelian then $M_k(\rho)$ generally does not decompose into $\bigoplus_{\chi} M_{k,\chi}(\rho)$.

Similarly the method

`w.invariant_cusp_forms_dimension(k, chi = chi)`

computes the dimension $\dim S_{k,\chi}(\rho)$ where $S_{k,\chi}(\rho) = M_{k,\chi}(\rho) \cap S_k(\rho)$.

The method

`w.invariant_forms_basis(k, prec, chi = chi)`

computes a WeilRepModularFormsBasis of $M_{k,\chi}(\rho)$ up to precision $prec$. Similarly the method

`w.invariant_cusp_forms_basis(k, prec, chi = chi)`

computes a WeilRepModularFormsBasis of $S_{k,\chi}(\rho)$ up to precision $prec$.

2.6 Quasimodular forms

See e.g. section 5.3 of [29] for an introduction to quasimodular forms. This extends immediately to vector-valued forms.

Let $A = (A, Q)$ be a discriminant form. A *quasimodular form* for the Weil representation of A is a holomorphic vector-valued function $f = f_0 : \mathbb{H} \rightarrow \mathbb{C}[A]$ with a Fourier expansion of the form

$$f(\tau) = \sum_{\gamma \in A} \sum_{n \in \mathbb{Z} - Q(\gamma)} c(n, \gamma) q^n \mathbf{e}_\gamma$$

with the property that there are finitely many holomorphic functions $f_1, \dots, f_d : \mathbb{H} \rightarrow \mathbb{C}[A]$ such that the *completion* of f_0 ,

$$F(\tau) = \sum_{r=0}^d f_r(\tau) (4\pi y)^{-r}$$

transforms like a modular form. The forms $f_i(\tau)$ are then also quasimodular forms.

Typical examples of quasimodular forms are theta series attached to non-harmonic polynomials; Eisenstein series of weight two; and derivatives (of any order) of holomorphic modular forms.

2.6.1 Completion

Suppose f is a quasimodular form. The completion of f to an almost-holomorphic modular form can be computed with the method

```
f.completion()
```

The result is a *WeilRepAlmostHolomorphicModularForm* instance that prints the nonholomorphic modular form $F(\tau)$ as in the following example:

```
w = WeilRep(matrix([[2, 0], [0, -2]]))
w.eisenstein_series(2, 5).completion()
```

yields

Almost holomorphic modular form $f_0 + f_1 * (4 \pi y)^{-1}$, where:

```
f_0 =
[(0, 0), 1 - 16*q - 24*q^2 - 64*q^3 - 72*q^4 + 0(q^5)]
[(1/2, 0), -16*q^(3/4) - 32*q^(7/4) - 48*q^(11/4) - 96*q^(15/4) - 80*q^(19/4) + 0(q^(23/4))]
[(0, 1/2), -4*q^(1/4) - 24*q^(5/4) - 52*q^(9/4) - 56*q^(13/4) - 72*q^(17/4) + 0(q^(21/4))]
[(1/2, 1/2), -8*q - 48*q^2 - 32*q^3 - 96*q^4 + 0(q^5)]
```

```
-----
f_1 =
[(0, 0), -6 + 0(q^5)]
[(1/2, 0), 0(q^(23/4))]
[(0, 1/2), 0(q^(21/4))]
[(1/2, 1/2), -6 + 0(q^5)]
```

Additionally, the completion of f acts as a list of quasimodular forms: in the above example, letting

```
X = w.eisenstein_series(2, 5).completion()
```

the terms f_0, f_1 can be accessed as $X[0], X[1]$. The first term f_0 can also be accessed as the holomorphic part:

```
X.holomorphic_part()
```

2.6.2 Other operations

Many (but not all) of the operations that apply to modular forms also apply to quasimodular forms. In particular, quasimodular forms can be added, multiplied (tensored), etc. The following additional features are useful. Suppose f is a quasimodular form.

`f.depth()`

computes the depth of f , i.e. the minimal $d \in \mathbb{N}$ such that $F(\tau) = \sum_{r=0}^d f_r(\tau)(4\pi y)^{-r}$ for some quasimodular forms f_r .

`f.shift()`

applies the map δ in section 5.3 of [29] i.e. it sends f to the term f_1 in its completion.

2.7 Mock modular forms

There is some support for vector-valued mock modular forms and harmonic Maass forms. For background see [6].

A harmonic weak Maass form of weight k is a real-analytic function $f : \mathbb{H} \rightarrow \mathbb{C}[A]$ satisfying the transformation rules

$$f(M \cdot \tau) = (c\tau + d)^k \rho(M) f(\tau), \quad M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, (c\tau + d)^{1/2} \in \text{Mp}_2(\mathbb{Z})$$

and a growth condition at ∞ and which solves the differential equation

$$\Delta_k f = 0,$$

where

$$\Delta_k = -4y^2 \frac{\partial^2}{\partial \tau \partial \bar{\tau}} + 2iky \frac{\partial}{\partial \tau}.$$

Such a function is represented by its Fourier series which takes the form

$$f(\tau) = \sum_{n \geq -N} a_f(n) q^n + b_f(0) y^{1-k} + \sum_{n < 0} b_f(n) \Gamma(1-k, 4\pi|n|y) q^n, \quad a_f(n), b_f(n) \in \mathbb{C}, \quad q = e^{2\pi i \tau}.$$

When $k = 1$ the term y^{1-k} must be replaced by $\log(y)$. Here $\Gamma(s, x) = \int_x^\infty e^{-t} t^{s-1} dt$ is the upper incomplete Gamma function; when computing numerically it may be better to write

$$\Gamma(1-k, 4\pi|n|y) q^n = U(k, k; 4\pi|n|y) e^{2\pi i |n|(-\bar{\tau})}$$

where U is the confluent hypergeometric U -function, as this is less likely to cause roundoff or overflow errors.

The *holomorphic part* of f ,

$$\sum_{n \geq -N} a_f(n)$$

is called a *mock modular form* of weight k . The remaining coefficients $b_f(n)$ can be expressed conveniently through a modular form of weight $2-k$ called the *shadow*:

$$\xi_k f(\tau) := 2i(-4\pi)^{k-1} y^k \overline{\partial_{\bar{\tau}} f(\tau)} = (1-k) \overline{b_f(0)} + \sum_{n > 0} \overline{b_f(-n)} n^{1-k} q^n.$$

(Warning: the factor $(-4\pi)^{k-1}$ is not always present in the references.) (Warning: when $k = 1$ the factor in front of $\overline{b_f(0)}$ is incorrect.)

The following constructions of modular forms are supported.

2.7.1 Zagier Eisenstein series

Suppose $L = (L, Q)$ is an even lattice whose signature is 1 mod 4 with WeilRep w . The value at $s = 0$ of the spectrally deformed Eisenstein series

$$E_{3/2}(\tau; s) = \sum_{M \in \Gamma_\infty \backslash \Gamma} (y^s \mathbf{e}_0) \Big|_{3/2, \rho} M = \frac{1}{2} \sum_{\substack{c, d \in \mathbb{Z} \\ \gcd(c, d) = 1}} \frac{y^s}{|c\tau + d|^{2s} (c\tau + d)^{3/2}} \rho(M)^{-1} \mathbf{e}_0,$$

(where $M \in \text{Mp}_2(\mathbb{Z})$ may be any element whose bottom row is c, d and whose square root branch agrees with the branch used in $(c\tau + d)^{3/2}$) is a harmonic Maass form (since Δ_k is self adjoint) but may fail to be holomorphic. In general the *Zagier Eisenstein series* is the holomorphic part of $E_{3/2}(\tau; 0)$.

The holomorphic part is the formal result of the Bruinier–Kuss formula [9] and the shadow can be computed as in [25].

Example. The original Zagier Eisenstein series appears when $L = \mathbb{Z}$ with norm $Q(x) = x^2$. We compute its completion to a Maass form with

```
WeilRep([[2]]).eisenstein_series(3/2, 10).completion()
```

which outputs

Harmonic Maass form with holomorphic part

$[(0), 1 - 6*q - 12*q^2 - 16*q^3 - 18*q^4 - 24*q^5 - 24*q^6 - 24*q^7 - 36*q^8 - 3$

$[(1/2), -4*q^(3/4) - 12*q^(7/4) - 12*q^(11/4) - 24*q^(15/4) - 12*q^(19/4) - 36*q$

and shadow $1/\pi$ times

$[(0), 3/2 + 3*q + 3*q^4 + 3*q^9 + 0(q^{10})]$

$[(1/2), 3*q^(1/4) + 3*q^(9/4) + 3*q^(25/4) + 0(q^(41/4))]$

From this one can read off that the nonholomorphic Fourier coefficients $b_f(n)$ are

$$b_f(0) = -\frac{3}{\pi}, \quad b_f(n^2) = \frac{3|n|}{\pi}, \quad n < 0, \quad b_f(n) = 0 \text{ otherwise.}$$

The coefficients of the holomorphic part are the Hurwitz class numbers $H(4n)$. Altogether

$$E_{3/2}(\tau; 0) = \sum_{n=0}^{\infty} H(n) q^{n/4} \mathbf{e}_{n/2} - \frac{3}{\pi\sqrt{y}} \mathbf{e}_0 - \frac{3}{2\pi\sqrt{y}} \sum_{\substack{n \in \mathbb{Z} \\ n \neq 0}} \left(\int_1^{\infty} t^{-3/2} e^{-\pi n^2 y t} dt \right) q^{-n^2/4} \mathbf{e}_{n/2}.$$

2.7.2 Maass Eisenstein series

Warning: this needs further testing when the weight is half-integral.

The *Maass Eisenstein series* $\tilde{E}_k(\tau)$ of weight $k < 0$ is the value at $s = 1 - k$ of $E_k(\tau; s) = \sum_{M \in \Gamma_\infty \backslash \Gamma} (y^s \mathbf{e}_0) \Big|_k M$. Since

$$\Delta_k E_k(\tau; s) = s(1 - k - s) E_k(\tau; s)$$

it follows that $\tilde{E}_k(\tau)$ is annihilated by Δ_k and therefore defines a harmonic Maass form. The *mock Eisenstein series* is its holomorphic part.

When k is an integer, (and in particular the underlying lattice $L = (L, Q)$ has even rank) the mock Eisenstein series has a Fourier expansion of the form

$$\pi^{k-1} \left(C + \sum_{n>0} c(n) q^n \right), \quad C \in \mathbb{C}[A], \quad c(n) \in \mathbb{Q}[A].$$

The constant term C involves non-critical values of quadratic L functions (or the Riemann zeta function) e.g. $\zeta(3)$ which probably cannot be simplified.

Non-critical values of quadratic L -functions are represented formally by

$$L(s, D) = \sum_{n=1}^{\infty} \chi_D(n) n^{-s}, \quad \chi_D(n) := \left(\frac{D}{n} \right).$$

More precisely these are instances of the QuadraticLFunction class from the file *weilrep_misc.py*, which is not available by default but can be imported manually. They can be evaluated numerically (using Pari/GP) with the usual *.n()*. These values are expressed in terms of the Riemann zeta function if possible (i.e. if D is a square).

The mock Eisenstein series of weight k to precision *prec* can be computed using

```
w.mock_eisenstein_series(k, prec)
```

Its completion to a harmonic Maass form can be computed using

```
w.maass_eisenstein_series(k, prec)
```

Example. The scalar-valued Maass Eisenstein series of weight (-2) for the full group $SL_2(\mathbb{Z})$ can be computed with

```
WeilRep([]).maass_eisenstein_series(-2, 5)
```

which yields

```
Harmonic Maass form with holomorphic part pi^(-3) times
-45/2*zeta(3) - 45/2*q - 405/16*q^2 - 70/3*q^3 - 3285/128*q^4 + 0(q^5)
and shadow
3 + 720*q + 6480*q^2 + 20160*q^3 + 52560*q^4 + 0(q^5)
```

Compare this with the explicit formula

$$\tilde{E}_{-2}(\tau) = y^3 - \frac{45}{2\pi^3} \left[\zeta(3) + \sum_{n=1}^{\infty} \sigma_{-3}(n) \left(q^n + \bar{q}^n (1 + 4\pi n y + 8\pi^2 n^2 y^2) \right) \right].$$

(Here $q = e^{2\pi i \tau}$ and $\bar{q} = e^{2\pi i (-\bar{\tau})}$, and $\tau = x + iy$.)

Example. Let (L, Q) be the lattice \mathbb{Z}^2 with Gram matrix $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$. The Maass Eisenstein series of weight (-1) is computed by typing

```
WeilRep([[2, 1], [1, 2]]).maass_eisenstein_series(-1, 5)
```

which outputs

```
Harmonic Maass form with holomorphic part pi^(-2) times
[(0, 0), -81/8*L(2, -3) - 9*q - 135/16*q^2 - 10*q^3 + 0(q^4)]
[(2/3, 2/3), -243/32*q^(2/3) - 243/25*q^(5/3) - 4131/512*q^(8/3) - 1215/121*q^(11/3) + 0(q^(14/3))]
[(1/3, 1/3), -243/32*q^(2/3) - 243/25*q^(5/3) - 4131/512*q^(8/3) - 1215/121*q^(11/3) + 0(q^(14/3))]
and shadow
[(0, 0), -2 + 180*q + 432*q^2 + 1476*q^3 + 0(q^4)]
[(1/3, 1/3), 18*q^(1/3) + 234*q^(4/3) + 900*q^(7/3) + 1296*q^(10/3) + 0(q^(13/3))]
[(2/3, 2/3), 18*q^(1/3) + 234*q^(4/3) + 900*q^(7/3) + 1296*q^(10/3) + 0(q^(13/3))]
```

Here the constant term of the holomorphic part involves the L -value

$$L(2, -3) = \sum_{n=1}^{\infty} \chi_{-3}(n) n^{-2} \approx 0.781302412896486.$$

To get a numerical approximation use the method `.n()`, i.e.

```
WeilRep([[2, 1], [1, 2]]).maass_eisenstein_series(-1, 2).n()
```

for which the output is:

Harmonic Maass form with holomorphic part

```
[(0, 0), -0.801520163230027 - 0.911890652781040*q + 0(q^2)]
[(2/3, 2/3), 0.000000000000000*q^(-1/3) - 0.769407738284002*q^(2/3) - 0.984841905003523*q^(5/3) + 0(q^(8/3))]
[(1/3, 1/3), 0.000000000000000*q^(-1/3) - 0.769407738284002*q^(2/3) - 0.984841905003523*q^(5/3) + 0(q^(8/3))]
and shadow
[(0, 0), -2.000000000000000 + 180.0000000000000*q + 0(q^2)]
[(1/3, 1/3), 0.000000000000000*q^(-2/3) + 18.0000000000000*q^(1/3) + 234.0000000000000*q^(4/3) + 0(q^(7/3))]
[(2/3, 2/3), 0.000000000000000*q^(-2/3) + 18.0000000000000*q^(1/3) + 234.0000000000000*q^(4/3) + 0(q^(7/3))]
```

(Note: the multiplier π^{-2} is applied automatically!)

2.7.3 Maass Poincaré series

Let (L, Q) be an even lattice and $\beta \in L'/L$. Let $m \in \mathbb{Z} - Q(\beta)$ be an index (similarly to the holomorphic Poincaré series) with $m < 0$. The **Maass Poincaré series** of weight $k \in \frac{1}{2}\mathbb{Z}$ (where k is integral if L has even rank; and k is half-integral otherwise) is defined by Poincaré averaging:

$$F_{k,m,\beta}(\tau) := \sum_{M \in \Gamma_{\infty} \backslash \Gamma} \left(\phi_{k,m}(\tau) \mathfrak{e}_{\beta} \right) \Big|_{k,\rho} M,$$

where

$$\phi_{k,m}(\tau) := (1 - k) \cdot q^m \gamma(1 - k, 4\pi|m|y), \quad \tau = x + iy$$

and γ is the *lower* incomplete Gamma function:

$$\gamma(s, z) := \int_0^z t^{s-1} e^{-t} dt = \Gamma(s) e^{-z} \sum_{n=0}^{\infty} \frac{z^{n+s}}{\Gamma(n+s+1)}, \quad \text{Re}[s] > 0.$$

This defines a harmonic weak Maass form whose shadow is (a simple multiple of) the Poincaré series $P_{k,-m,\beta}$ for the Weil representation associated to the lattice $(L, -Q)$.

Similarly to the method `poincare_series()` it can be computed by calling

```
w.maass_poincare_series(k, b, m, prec, nterms = 50)
```

where $b = \beta$ is the appropriate element of L'/L ; m is the index; `prec` is the precision (the highest power of q in the Fourier expansion); and `nterms` is the number of terms used in the coefficient formula (an infinite sum over values of Bessel functions and Kloosterman sums, cf. Proposition 1.9 of [7]); by default we compute using the first 50 terms in this series. The holomorphic part can be called with

```
w.mock_poincare_series(k, b, m, prec, nterms = 50)
```

The first Fourier coefficients are generally more accurate.

Example. The scalar-valued Maass Poincaré series of weight (-2) and index (-1) , using the first 50 terms in the coefficient formula. Input:

```
WeilRep([]).maass_poincare_series(-2, vector([]), -1, 2)
```

Output:

Harmonic weak Maass form with holomorphic part

```
1.0000000000000000*q^-1 - 240.00000000000000 - 141443.999817774*q - 8.52927999981621e6*q^2 + 0(q^3)
and shadow
```

```
0.0000000000000000 + 0.318058316204658*q - 3.75224055055394*q^2 + 0(q^3)
```

In fact, the Maass Poincaré series is

$$E_{10}(\tau)/\Delta(\tau) = q^{-1} - 240 - 141444q - 8529280q^2 - \dots$$

and the shadow is zero.

2.8 Visualization

The *plot()* and *plot_q()* methods provide phase plots of vector-valued modular forms. This is inspired by the paper [18] which considers plotting modular forms in much more detail.

Suppose f is a vector-valued modular form (or quasi-modular form; almost-holomorphic modular form; mock modular form; etc.) The method

```
f.plot()
```

by default creates a list of complex plots for each of the components of $f(\tau)$ on the domain

$$\{\tau = x + iy : -1 \leq x \leq 1, 0 < y \leq 2\}.$$

This accepts all optional arguments for Sage's *complex_plot()* (e.g. *plot_points*, *show_axes*, etc.) as well as the following optional arguments:

x_range: the range for x (by default $[-1, 1]$);

y_range: the range for y (by default $[0.01, 2]$);

show: a Boolean (default True). If True, then we attempt to show all plots as they are created, with a description of the vector component, before returning the list of plots.

isotherm: a Boolean (default True). If True then the magnitude of f is indicated by isotherm lines rather than brightness.

function: if this is given, it should be a function that accepts complex vectors and outputs complex numbers. We apply this function first and then plot. For example to sum the components together use

```
f.plot(function = sum)
```

Most forms can be plotted to reasonable accuracy with very few Fourier coefficients. To get better pictures it is usually more important to adjust the *plot_points* parameter.

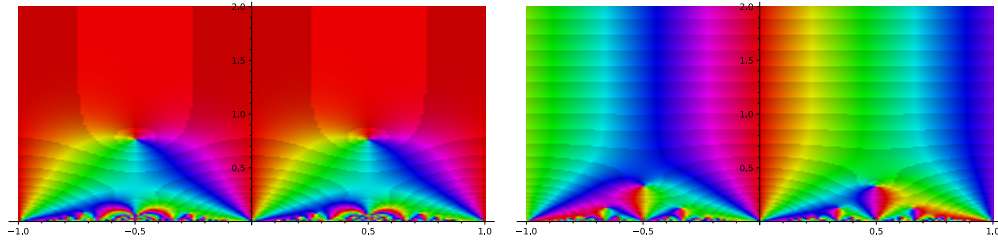
Example. The Cohen Eisenstein series of weight $7/2$ can be constructed as a vector-valued modular form to precision $O(q^5)$, i.e.

$$(1 + 126q + 756q^2 + 2072q^3 + 4158q^4 + \dots)\mathfrak{e}_0 + (56q^{3/4} + 576q^{7/4} + 1512q^{11/4} + 4032q^{15/4} + 5544q^{19/4} + \dots)\mathfrak{e}_{1/2}$$

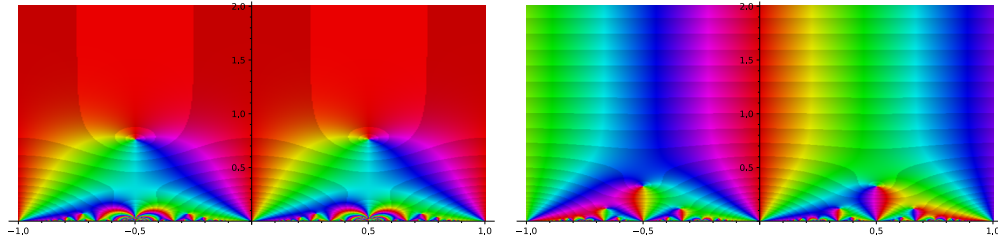
by entering

```
f = WeilRep([2]).eisenstein_series(7/2, 5)
```

Plotting with default settings (i.e. *f.plot()*) yields the pictures



for the components of ϵ_0 and $\epsilon_{1/2}$, respectively. Raising the parameter *plot_points* to 400 yields the better pictures



Both examples use only the first five Fourier coefficients.

The method

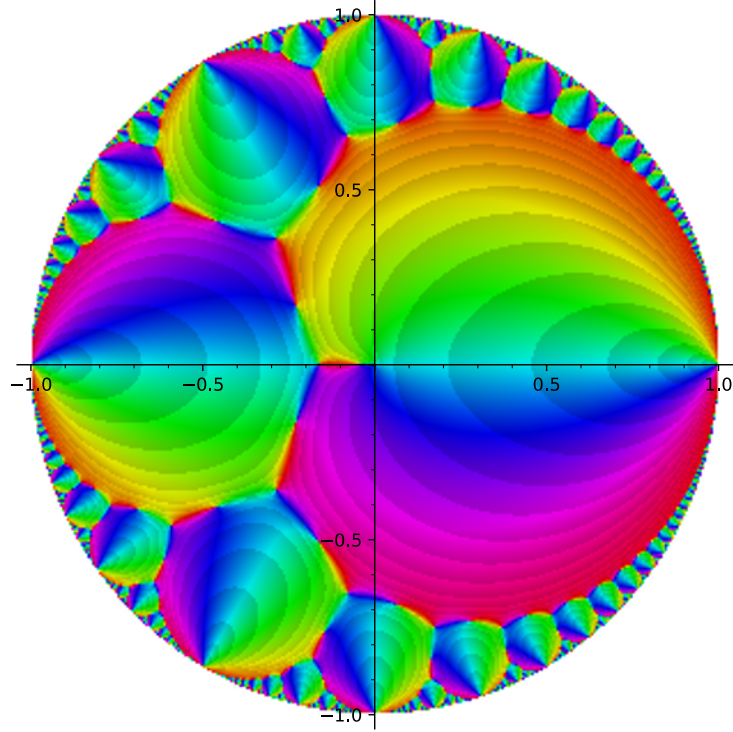
`f.plot_q()`

creates a similar list of complex plots of the components of f ; this time as functions of q on the unit disc. This accepts the same optional parameters as *f.plot()*, with the exception of *x_range* and *y_range* (which are both fixed to $[-1, 1]$).

Example. A plot of the scalar Maass Eisenstein series of weight -2 . Entering

```
f = WeilRep([]).maass_eisenstein_series(-2, 5)
f.plot_q(plot_points = 300)
```

produces the image



3 Jacobi forms

Let $M = (M, Q)$ be a positive-definite even lattice. A *Jacobi form* of weight $k \in \mathbb{Z}$ and index M is a holomorphic function

$$\phi = \phi(\tau, z) : \mathbb{H} \times (M \otimes \mathbb{C}) \longrightarrow \mathbb{C}$$

that satisfies

$$\phi\left(\frac{a\tau + b}{c\tau + d}, \frac{z}{c\tau + d}\right) = (c\tau + d)^k \exp\left(2\pi i Q(z)c/(c\tau + d)\right) \phi(\tau, z)$$

for all $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z})$, and

$$\phi(\tau, z + \tau\lambda) = \exp\left(-2\pi i \tau Q(\lambda) - \langle \lambda, z \rangle\right) \phi(\tau, z), \quad \phi(\tau, z + \lambda) = \phi(\tau, z)$$

for all $\lambda \in M$, as well as a vanishing condition on Fourier coefficients: the expansion of ϕ takes the form

$$\phi(\tau, z) = \sum_{n=0}^{\infty} \sum_{\lambda \in M'} c(\lambda, n) q^n \zeta^\lambda, \quad q := e^{2\pi i \tau}, \quad \zeta^\lambda := e^{2\pi i \langle \lambda, z \rangle},$$

and $c(\lambda, n) = 0$ if $Q(\lambda) > n$.

Jacobi forms of scalar index $m \in \mathbb{N}$ (as in [13]) are the same as Jacobi forms for the lattice $M = \mathbb{Z}$ with quadratic form $Q(x) = mx^2$.

Construct the module of Jacobi forms of index m with

`JacobiForms(m)`

where m is either a positive-definite Gram matrix or a positive integer.

3.1 Basic attributes

Let

```
j = JacobiForms(m)
```

be a JacobiForms instance. The following basic attributes can be computed.

3.1.1 Index

```
j.index()
```

returns the index (as a matrix, or as a number if the matrix is one-dimensional).

```
j.index_matrix()
```

always returns the index as a matrix.

3.1.2 Weil representation

```
j.theta_decomposition()
```

returns the Weil representation corresponding to this module of Jacobi forms.

3.2 Construction of Jacobi forms

Suppose j is a JacobiForms instance: $j = \text{JacobiForms}(m)$.

3.2.1 Jacobi Eisenstein series

The Jacobi Eisenstein series is the sum

$$\sum_{M \in \mathcal{J}_\infty \backslash \mathcal{J}} 1 \Big|_{k,m} M,$$

where \mathcal{J} is the Jacobi group and \mathcal{J}_∞ the stabilizer of ∞ , and $|_{k,m}$ is the Petersson slash operator. cf. chapter 2 of [13].

```
j.eisenstein_series(k, prec)
```

computes the Jacobi Eisenstein series of weight k to precision $prec$ (with respect to the $q = e^{2\pi i \tau}$ variable). For example the Jacobi Eisenstein series $E_{4,1}$ of weight 4 and index 1 can be computed to precision $O(q^5)$ with

```
JacobiForms(1).eisenstein_series(4, 5)
```

More directly,

```
jacobi_eisenstein_series(k, m, prec)
```

constructs the Jacobi Eisenstein series of weight k and index m .

Similarly the commands

```
j.eisenstein_oldform()
```

and

```
j.eisenstein_newform()
```

can be used to compute other Eisenstein series.

3.2.2 Theta blocks

Theta blocks were introduced in [15]. For $\mathbf{a} = (a_1, \dots, a_r) \in \mathbb{Z} \setminus \{0\}$ and $n \in \mathbb{Z}$ define

$$\vartheta_{\mathbf{a},n} := \eta^n(\tau) \prod_{i=1}^r \vartheta(\tau, a_i z)$$

where

$$\eta(\tau) = q^{1/24} \prod_{n=1}^{\infty} (1 - q^n) = \sum_{n=1}^{\infty} \binom{12}{n} q^{n^2/24}$$

and

$$\vartheta(\tau, z) = q^{1/8} \zeta^{1/2} \prod_{n=1}^{\infty} (1 - q^n)(1 - q^n \zeta)(1 - q^{n-1} \zeta^{-1}) = \sum_{n \in \mathbb{Z}} \binom{-4}{n} q^{n^2/8} \zeta^{n/2}.$$

When $\sum_{i=1}^r a_i$ is even and $r/8 + n/24 \in \mathbb{Z}$ this transforms like a Jacobi form. (Whether it is holomorphic in the cusps is a trickier point.)

Theta blocks are implemented with the command `theta_block(a,n,prec)`.

Example (from [15]). The (unique, up to scalar) Jacobi form of weight 2 and index 25 is the theta block with $\mathbf{a} = [1, 1, 1, 1, 2, 2, 2, 3, 3, 4]$ and $n = -6$. To compute it (here only to precision $O(q^2)$): Input:

```
print(theta_block([1,1,1,1,2,2,2,3,3,4],-6,2))
```

Output:

```
(w_0^-10 - 4*w_0^-9 + 3*w_0^-8 + 6*w_0^-7 - 7*w_0^-6 - 2*w_0^-5 - 4*w_0^-4 + 10*w_0^-3 + 6*w_0^-2
- 10*w_0^-1 + 2 - 10*w_0 + 6*w_0^2 + 10*w_0^3 - 4*w_0^4 - 2*w_0^5 - 7*w_0^6 + 6*w_0^7 + 3*w_0^8
- 4*w_0^9 + w_0^10)*q + 0(q^2)
```

3.2.3 Theta blocks associated to root systems

Let R be a root system with a system of positive roots R_+ and simple roots Δ . Gritsenko, Skoruppa, Zagier [15] associate to R a Jacobi form of lattice index:

$$\vartheta_R(\tau, z) = \eta(\tau)^{\text{rank}(R) - |R_+|} \prod_{\alpha \in R_+} \vartheta\left(\tau, \sum_{\beta \in \Delta} c_\alpha(\beta) z_\beta\right),$$

where $\alpha = \sum_{\beta \in \Delta} c_\alpha(\beta) \beta$, and where $z_\beta, \beta \in \Delta$ are complex variables. This form has weight $\text{rank}(R)/2$ and transforms with the $(\text{rank}(R) + 2|R_+|)$ -power of the eta multiplier.

It is implemented with

```
root_lattice_theta_block(R, prec)
```

where R is a RootSystem and `prec` is the desired precision.

Example. The theta block associated to the root system A_2 , to precision 5:

```
root_lattice_theta_block(RootSystem(['A', 2]), 5)
```


3.2.4 Jacobi Poincaré series

`j.poincare_series(k, n, r, prec, nterms)`

computes the Jacobi Poincaré series:

$$f(\tau, z) = \sum_{M \in \mathcal{J}_\infty \setminus \mathcal{J}} (q^n \zeta^r) \Big|_{k, m} M$$

of index (n, r) . Here $n \in \mathbb{Z}$ should be an integer and $r \in \mathbb{Z}^N$ should be a vector (or an integer, if $N = 1$), where N is the index rank i.e. number of abelian variables. The procedure is the same as the vector-valued Poincaré series: the Fourier coefficients are series over Bessel function values and Kloosterman sums, and we compute approximations by truncating these series at *nterms*.

3.2.5 Jacobi forms from vector-valued modular forms

If f is a vector-valued modular form for the Weil representation attached to a positive-definite Gram matrix m , then f comes with the method

`f.jacobi_form()`

which produces the Jacobi form of index m whose theta decomposition is f itself.

3.3 Spaces of Jacobi forms

Again let

`j = JacobiForms(m)`

be a `JacobiForms` instance.

3.3.1 Jacobi forms

The method

`j.basis(k, prec)`

computes a basis of (holomorphic) Jacobi forms of weight k for the given index with Fourier expansions to precision *prec* (with respect to the $q = e^{2\pi i \tau}$ variable).

Generally we use whatever methods are available to compute bases of spaces of vector-valued modular forms and then pass to the associated Jacobi forms. For scalar-index Jacobi forms of low weights (2 and 3) we sometimes look through families of theta blocks first.

The method

`j.dimension(k)`

computes the dimension of the space of (holomorphic) Jacobi forms of weight k using the Riemann-Roch formula.

Jacobi forms of all weights form a finite free $\mathbb{C}[E_4, E_6]$ -module so the Hilbert series of dimensions has the form

$$\text{Hilb} = \sum_{k \geq 0} \dim J_k t^k = \frac{P(t)}{(1 - t^4)(1 - t^6)}$$

for some polynomial $P \in \mathbb{C}[t]$. The method

`j.hilbert_series()`

computes the Hilbert series as a power series. The method

`j.hilbert_polynomial()`

computes the polynomial P .

3.3.2 Cusp forms

The method

`j.cusp_forms_basis(k, prec)`

computes a basis of Jacobi cusp forms of weight k for the given index with Fourier expansions to precision $prec$ (with respect to the $q = e^{2\pi i\tau}$ variable).

Generally we use whatever methods are available to compute bases of spaces of vector-valued cusp forms and then pass to the associated Jacobi forms. For scalar-index Jacobi forms of low weights (2 and 3) we sometimes look through families of theta blocks first.

The method

`j.cusp_forms_dimension(k)`

computes the dimension of the space of Jacobi cusp forms of weight k using the Riemann-Roch formula.

3.3.3 Weak Jacobi forms

A weak Jacobi form is a holomorphic function that transforms like a Jacobi form and has Fourier expansion of the form

$$\phi(\tau, z) = \sum_{n=0}^{\infty} \sum_r c(n, r) q^n \zeta^r$$

but without restrictions on r .

The method

`j.weak_forms_basis(k, prec)`

computes a basis of weak Jacobi forms of weight k for the given index with Fourier expansions to precision $prec$. (Here the weight k may be negative!)

The method

`j.weak_forms_dimension(k)`

computes the dimension J_k^w of the space of weak Jacobi forms of weight k .

Weak Jacobi forms of all weights form a finite free $\mathbb{C}[E_4, E_6]$ -module, so the Hilbert series of dimensions has the form

$$\text{Hilb}^w = \sum_{k \gg -\infty} \dim J_k^w t^k = \frac{P(t)}{(1-t^4)(1-t^6)}$$

for some Laurent polynomial $P \in \mathbb{C}[t, t^{-1}]$. The method

`j.weak_hilbert_series()`

computes the weak Hilbert series Hilb^w as a power series. The method

`j.weak_hilbert_polynomial()`

computes the Laurent polynomial P .

3.4 Jacobi forms on congruence subgroups

3.4.1 Jacobi forms on congruence subgroups

Let $\Gamma \leq \mathrm{SL}_2(\mathbb{Z})$ be a congruence subgroup. A Jacobi form of weight k and index (M, Q) is a holomorphic function

$$\phi = \phi(\tau, z) : \mathbb{H} \times (M \otimes \mathbb{C}) \longrightarrow \mathbb{C}$$

that satisfies the quasi-ellipticity equations

$$\phi(\tau, z + \tau\lambda) = \exp\left(-2\pi i\tau Q(\lambda) - \langle \lambda, z \rangle\right) \phi(\tau, z), \quad \phi(\tau, z + \lambda) = \phi(\tau, z),$$

but for which the functional equation

$$\phi\left(\frac{a\tau + b}{c\tau + d}, \frac{z}{c\tau + d}\right) = (c\tau + d)^k \exp\left(2\pi i Q(z)c/(c\tau + d)\right) \phi(\tau, z)$$

need only hold for $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \Gamma$. There is also a growth condition which must hold at all cusps of Γ .

To construct Jacobi forms of level $\Gamma = \Gamma_0(N)$, $\Gamma_1(N)$ or $\Gamma(N)$ and index M , write

`J = JacobiForms(Gamma0(N), M)`

with `Gamma0` replaced by `Gamma1` or `Gamma` as necessary. Here, M can be either a positive-definite integral matrix with even integral diagonal, or a natural number m (in which case M is the 1×1 matrix $(2m)$). The empty case

`J = JacobiForms(Gamma0(N), matrix([]))`

corresponds to the usual notion of modular forms of level Γ .

3.4.2 Spaces of Jacobi forms

Bases of modular forms and cusp forms are computed using the same syntax as level one. For example,

`JacobiForms(Gamma0(3), 4).basis(8, 10)`

will compute a basis of the twelve-dimensional space

$$J_{8,4}(\Gamma_0(3))$$

of Jacobi forms of weight **8** and index **4** which transform under the group $\Gamma_0(3)$, each up to precision **10**.

3.4.3 Jacobi theta functions

The four Jacobi theta functions are Jacobi forms of weight $1/2$ and index $1/2$ that are modular under the group $\Gamma(2)$. We use the following notation:

$$\begin{aligned} \theta_{00}(\tau, z) &= \sum_{n \in \mathbb{Z}} q^{n^2/2} \zeta^n = 1 + (\zeta^{-1} + \zeta)q^{1/2} + (\zeta^{-2} + \zeta^2)q^2 + \dots \\ \theta_{01}(\tau, z) &= \sum_{n \in \mathbb{Z}} (-1)^n q^{n^2/2} \zeta^n = 1 - (\zeta^{-1} + \zeta)q^{1/2} + (\zeta^{-2} + \zeta^2)q^2 \pm \dots \\ \theta_{10}(\tau, z) &= \sum_{n \in \frac{1}{2} + \mathbb{Z}} q^{n^2/2} \zeta^n = (\zeta^{-1/2} + \zeta^{1/2})q^{1/8} + (\zeta^{-3/2} + \zeta^{3/2})q^{9/8} + \dots \\ \theta_{11}(\tau, z) &= \sum_{n \in \frac{1}{2} + \mathbb{Z}} (-1)^{n-1/2} q^{n^2/2} \zeta^n = (\zeta^{1/2} - \zeta^{-1/2})q^{1/8} - (\zeta^{3/2} - \zeta^{-3/2})q^{9/8} \pm \dots \end{aligned}$$

The Jacobi theta functions are implemented with the command

```
jacobi_theta_series(prec, 's')
```

where $prec$ is the precision (with respect to q) and where s is one of the strings 00, 01, 10 or 11.

The Jacobi thetanulls are the zero values

$$\theta_{00}(\tau, 0), \quad \theta_{01}(\tau, 0), \quad \theta_{10}(\tau, 0)$$

and they are implemented as Jacobi forms whose index is the rank 0 lattice. Note that $\theta_{11}(\tau, 0)$ vanishes. The Jacobi thetanulls are implemented with the command

```
jacobi_thetanull(prec, 's')
```

where $prec$ is the precision (with respect to q) and where s is one of the strings 00, 01 or 10.

3.5 Operations on Jacobi forms

3.5.1 Arithmetic operations

Jacobi forms of the same weight and index can be added and subtracted. Jacobi forms whose indices have the same rank can be multiplied in the usual way. Also Jacobi forms can be multiplied by modular forms (i.e. `ModularFormElements`).

3.5.2 Development coefficients

Suppose f is a scalar-index Jacobi form. The *development coefficients* D_N ([13], Chapter 3) can be computed with the method

```
f.development_coefficient(N)
```

For example, to compute the second development coefficient of the normalized Jacobi cusp form of index 1 and weight 10, enter

```
JacobiForms(1).cusp_forms_basis(10, 10)[0].development_coefficient(2)
```

For lattice-index Jacobi forms, the development coefficients are defined through the theta decomposition using the development coefficients defined on vector-valued modular forms (cf. section 2.3).

3.5.3 Direct product

Call the *direct product* of two Jacobi forms f (of index m_1) and g (of index m_2) the Jacobi form in $\text{rank}(m_1) + \text{rank}(m_2)$ elliptic variables obtained by inserting distinct elliptic variables in f and g and multiplying i.e.

$$(f \times g)(\tau, (z_1, z_2)) = f(\tau, z_1) \cdot g(\tau, z_2).$$

This is a Jacobi form of index $m_1 \oplus m_2$. It is implemented as the operation `**`.

Example. Let $E_{4,1}$ be the Jacobi Eisenstein series of weight 4 and index 1. We will take its direct product with itself. Input:

```
E41 = jacobi_eisenstein_series(4,1,2)
E41 ** E41
```

Output:

$$1 + (w_0^2 + w_1^2 + 56w_0 + 56w_1 + 252 + 56w_1^{-1} + 56w_0^{-1} + w_1^{-2} + w_0^{-2})q + O(q^2)$$

3.5.4 Hecke operators

The Hecke operators T_N are currently only implemented for values N that are coprime to the level of the lattice. (Warning: when the index m is a scalar then the level is $4m!$) This is the method `hecke_T(N)`. The formula is taken from section 2.6 of A. Ajouz's thesis [1].

Example. The image of $E_{4,1}$ under T_3 . Input:

```
E41 = jacobi_eisenstein_series(4, 1, 40)
print(E41.hecke_T(3))
```

The Hecke U -operators are defined by

$$(\phi|U_N)(\tau, z) = \phi(\tau, Nz).$$

If ϕ has index m then $\phi|U_N$ has index N^2m . This is implemented with the method `hecke_U(N)`.

Example. The image of $E_{4,1}$ under U_2 . Input:

```
E41 = jacobi_eisenstein_series(4,1,3)
print(E41.hecke_U(2))
```

Output:

```
1 + (w_0^-4 + 56*w_0^-2 + 126 + 56*w_0^2 + w_0^4)*q
+ (126*w_0^-4 + 576*w_0^-2 + 756 + 576*w_0^2 + 126*w_0^4)*q^2 + 0(q^3)
```

The Hecke V -operators are defined by

$$(\phi|V_N)(\tau, z) = N^{k-1} \sum_M (c\tau + d)^{-k} e^{-2\pi i N c Q(z)/(c\tau + d)} \phi\left(\frac{a\tau + b}{c\tau + d}, \frac{Nz}{c\tau + d}\right)$$

where $M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ runs through $\mathrm{SL}_2(\mathbb{Z})$ -cosets of matrices with integer entries and determinant N . If ϕ has index m then $\phi|V_N$ has index Nm . This is implemented with the method `hecke_V(N)`.

Example. The image of $E_{4,1}$ under V_2 . Input:

```
E41 = jacobi_eisenstein_series(4,1,5)
print(E41.hecke_V(2))
```

Output:

```
9 + (126*w_0^-2 + 576*w_0^-1 + 756 + 576*w_0 + 126*w_0^2)*q
+ (9*w_0^-4 + 576*w_0^-3 + 2520*w_0^-2 + 4032*w_0^-1 + 5166 + 4032*w_0 + 2520*w_0^2 + 576*w_0^3 + 9*w_0^4)*q^2
+ 0(q^3)
```

3.5.5 is_cusp_form, is_holomorphic

Suppose f is a (weak, weakly holomorphic) Jacobi form. The methods `f.is_cusp_form()` and `f.is_holomorphic()` attempt to determine from the Fourier expansion of f whether f is a cusp form resp. a holomorphic Jacobi form.

Note: unlike regular modular forms, these properties cannot be determined from the q -expansion up to exponent 0. The methods `f.is_cusp_form()` and `f.is_holomorphic()` are rigorous - we do not guess! If we cannot determine whether the form is holomorphic (or cuspidal) from the known coefficients then we raise a `ValueError` (and suggest a better precision to use).

3.5.6 Linear relations

To compute the space of linear relations among Jacobi forms f_1, \dots, f_N of the same weight and the same index, use the method

```
relations(f_1, ..., f_N)
```

Warning: this uses only the known Fourier coefficients! If f_1, \dots, f_N have low precision then the result may be incorrect.

3.5.7 Pullback

Let $f(\tau, \mathbf{z})$ be a Jacobi form with $\mathbf{z} \in \mathbb{C}^d$ and let $a \in \mathbb{Z}^{c \times d}$ be a matrix of rank c . The method `pullback(a)` computes the Jacobi form $f(\tau, a\mathbf{z})$. If f has index m then its pullback along a has index ama^T (and the same weight).

Example. The pullback of the weight 4 Jacobi Eisenstein series of index $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$ along the matrix $a = (1, 2)$ is a Jacobi form of index 7. Input:

```
f = jacobi_eisenstein_series(4, matrix([[2, 1], [1, 2]]), 2)
f.pullback(matrix([[1, 2]]))
```

Output:

```
1 + (w_0^-5 + w_0^-4 + 27*w_0^-3 + 27*w_0^-2 + 28*w_0^-1 + 72
+ 28*w_0 + 27*w_0^2 + 27*w_0^3 + w_0^4 + w_0^5)*q + O(q^2)
```

3.5.8 Theta decomposition

The method

```
f.theta_decomposition()
```

returns the Theta decomposition of a Jacobi form f as a vector-valued modular form, cf. chapter 5 of [13].

3.5.9 Zero-values

Let $f(\tau, z_0, \dots, z_{d-1})$ be a Jacobi form in d elliptic variables. The method `substitute_zero(indices)` returns the Jacobi form obtained by setting some subset of the z_i to zero. (In other words setting $w_i = e^{2\pi iz_i}$ to 1.) `indices` should be a list containing distinct numbers between 0 and $d - 1$.

Example. The zero-value of the Jacobi Eisenstein series of weight four and index 1. Input:

```
E41 = jacobi_eisenstein_series(4, 1, 5)
E41.substitute_zero([0])
```

Output:

```
1 + 240*q + 2160*q^2 + 6720*q^3 + 17520*q^4 + O(q^5)
```

(This is a JacobiForm instance of index (empty matrix).)

The higher Taylor coefficients about zero are not (yet?) implemented.

3.6 Recovering Fourier coefficients from Jacobi forms

Let f be a `JacobiForm` instance.

The method

`f.coefficient_vector()`

outputs the Fourier coefficients $c(n, r)$ of f without redundancy as a vector sorted by increasing value of $n - r^2/4m$ (and its generalization to lattice index Jacobi forms).

The method

`f.q_coefficients()`

outputs the Fourier coefficients of f with respect to q *only* as a list of multivariate Laurent polynomials in variables $w_i = e^{2\pi i z_i}$.

The method

`f.fourier_expansion()`

outputs the Fourier expansion of f as a power series in q .

4 Modular forms on orthogonal groups

The class *OrthogonalModularForms* represents spaces of modular forms on the Type IV domain attached to an even lattice (L, Q) . We only allow lattices that are split by a hyperbolic plane over \mathbb{Z} ; i.e. those of the form

$$L = L_0 \oplus H$$

where H is the hyperbolic plane (\mathbb{Z}^2 with quadratic form $(x, y) \mapsto xy$) and where L_0 is Lorentzian. In this section we only consider the case where L_0 is itself of the form $K \oplus H$ with K positive-definite; for general L see the next chapter.

An *OrthogonalModularForms* instance can be constructed by calling

`OrthogonalModularForms(S)`

where S is a Gram matrix for the *positive-definite* part K , or

`OrthogonalModularForms(w)`

where w is a `WeilRep` instance for a positive-definite quadratic form.

Orthogonal modular forms for the Gram matrix S (of rank n) have Fourier expansions of the form

$$f(Z) = f(\tau, z, w) = \sum_{a,c=0}^{\infty} \sum_{b \in L} \alpha(a, b, c) q^a r^b s^c,$$

where $\tau, w \in \mathbb{H}$ and $z \in \mathbb{C}^n$ with $Q(\text{im}(z)) < \text{im}(\tau) \cdot \text{im}(w)$, and where $q = e^{2\pi i \tau}$, $r = e^{2\pi i b^T z}$ and $s = e^{2\pi i w}$.

Note:

`ParamodularForms(N)`

is a shortcut for the `OrthogonalModularForms` instance with Gram matrix $S = ((2N))$.

Throughout this section we let Γ_L denote the *orthogonal modular group* attached to L . Here this means the group

$$\Gamma_L = \ker\left(\mathrm{O}^+(L) \longrightarrow \mathrm{Aut}(L'/L)\right),$$

where $\mathrm{O}^+(L)$ is the *spinor kernel*: the intersection $\mathrm{O}(L) \cap \mathrm{O}^+(L \otimes \mathbb{R})$ where $\mathrm{O}^+(L \otimes \mathbb{R})$ is the group generated by reflections along positive-norm vectors in $L \otimes \mathbb{R}$.

4.1 Construction of modular forms

Let

```
m = OrthogonalModularForms(S)
```

be an orthogonal modular forms instance.

4.1.1 Eisenstein series

The method

```
m.eisenstein_series(k, prec)
```

computes the weight k Eisenstein series

$$E_k(Z) = \sum_{M \in \Gamma_{L,\infty} \setminus \Gamma_L} j(M; Z)^{-k},$$

where Γ_L is the orthogonal modular group; $j(M; Z)$ is the cocycle; and $\Gamma_{L,\infty}$ is the subgroup of Γ_S that leaves the constant 1 invariant. (Note: this is actually computed as a theta lift in the sense of section 4.1.2.)

Here k should be an even integer (sufficiently large) and $prec$ denotes the precision with respect to both q and s .

Example. The Siegel Eisenstein series of degree 2 and weight 4 up to precision 5. Input:

```
ParamodularForms(1).eisenstein_series(4, 5)
```

4.1.2 Additive theta lift

Let K be a positive-definite even lattice of rank n and let $M_k(\Gamma_L)$ denote the space of modular forms of weight k for the Type IV domain attached to $L = K \oplus \Pi_{2,2}$. The additive theta lift is a linear map

$$\Phi : M_{k-n/2}(\rho_K) \longrightarrow M_k(\Gamma_L).$$

The map Φ takes cusp forms to cusp forms. This is implemented with the method `theta_lift()`.

Example. The theta lift of the weight 8 cusp form attached to the A_2 root lattice. Input:

```
w = WeilRep(matrix([[2, 1], [1, 2]]))
f = w.cusp_forms_basis(8, 5)[0]
f.theta_lift()
```


Modular forms with poles at ∞ lift to meromorphic orthogonal modular forms with poles on Heegner divisors, by Theorem 14.3 of [3]. The Fourier expansion of meromorphic additive lifts takes the form

$$c_{0,0}(r) + \sum_{\substack{m,n \in \mathbb{N}_0 \\ (m,n) \neq (0,0)}} c_{m,n}(r) q^m s^n,$$

where all $c_{m,n}(r)$, $(m,n) \neq (0,0)$ are Laurent polynomials. $c_{0,0}(r)$ is a rational function of r which is not necessarily a Laurent polynomial.

Example. There is a singular theta lift of weight two for $\mathrm{Sp}_4(\mathbb{Z})$ with double poles on the diagonal in the Siegel half-space \mathbb{H}_2 . This corresponds to the Gram matrix $\mathbf{S} = (2)$. Write

```
w = WeilRep([[2]])
f = w.nearly_holomorphic_modular_forms_basis(3/2, 1/4, 5)[0]
12 * f.theta_lift().reduce_precision(3)
```

Output:

```
(r^2 + 10*r + 1)/(r^2 - 2*r + 1) + (12*r^-1 - 24 + 12*r)*q + (12*r^-1 - 24 + 12*r)*s
+ (24*r^-2 + 12*r^-1 - 72 + 12*r + 24*r^2)*q^2
+ (-24*r^-2 + 2976*r^-1 - 5904 + 2976*r - 24*r^2)*q*s
+ (24*r^-2 + 12*r^-1 - 72 + 12*r + 24*r^2)*s^2 + 0(q, s)^3
```

4.1.3 Borchers lift

Let K be a positive-definite even lattice of rank n . The Borchers lift [3] is a multiplicative map

$$\Phi : M_{-n/2}^! (\rho_K) \longrightarrow M_*(\Gamma_L)$$

where $M_{-n/2}^!$ denotes nearly-holomorphic modular forms. The result may transform with a character. This is implemented with the method *borchers_lift()*.

Example. The product of the ten even theta characteristics is a Siegel modular form of degree two with weight 5 with a character of order two. To construct it as a Borchers product: input

```
w = WeilRep(matrix([[2]]))
f = w.nearly_holomorphic_modular_forms_basis(-1/2, 1/4, 5)[0]
f.borchers_lift()
```

4.1.4 Gritsenko lift

If f is a Jacobi form then its Gritsenko lift

$$\Phi(f) = \sum_{n=0}^{\infty} (f|V_n) s^n$$

is an orthogonal modular form of the same weight. This is closely related to the additive theta lift. It is implemented with the method *gritsenko_lift()*.

Example. The Gritsenko lift of the Jacobi cusp form of index 2 and weight 11. Input:

```
f = JacobiForms(2).cusp_forms_basis(11, 5)[0]
f.gritsenko_lift()
```

4.1.5 Spezialschar

The method *spezialschar*(*k*, *prec*) computes a basis of the Maass Spezialschar of weight *k* to precision *prec* (i.e. cusp forms which are additive lifts).

Example. The Spezialschar of Siegel modular forms of degree two and weight 10. Input:

```
ParamodularForms(1).spezialschar(10, 5)
```

Calling *spezialschar* with no arguments produces the Maass Spezialschar as an abstract object. This can be used to test whether a modular form is a lift. For example, construct the Siegel modular form Borchers product of weight 24 as follows:

```
f = WeilRep([2]).nearly_holomorphic_modular_forms_basis(-1/2, 5/4, 10)[2]
f = f.borchers_lift()
```

and test whether it is a Maass lift (it is not) using

```
f in ParamodularForms(1).spezialschar()
```

4.2 Representations of modular forms

4.2.1 Fourier expansion

The Fourier expansion of the modular form can be recovered with *fourier_expansion*(*f*). The result is a power series in variables *q*, *s* over a ring of Laurent polynomials in the variables r_0, \dots, r_{n-1} where *n* is the rank of the lattice.

4.2.2 Fourier–Jacobi expansion

The Fourier–Jacobi expansion of the modular form *f* is the representation

$$f(\tau, z, w) = \sum_{n=0}^{\infty} \phi_n(\tau, z) s^n, \quad s = e^{2\pi i w}$$

where each ϕ_n is a Jacobi form of the same weight. This is implemented with *fourier_jacobi*(*f*). The result is a list of JacobiForm instances.

Example. The Fourier–Jacobi expansion of the Siegel Eisenstein series of degree 2 and weight 4. Input:

```
E4 = ParamodularForms(1).eisenstein_series(4, 5)
E4.fourier_jacobi()
```

4.2.3 Coefficient dictionary

The method *coefficients*(*f*) produces a dictionary of the modular form *f*’s Fourier coefficients.

4.3 Inputs for Borchers products

Let

```
m = OrthogonalModularForms(S)
```

be an OrthogonalModularForms instance.

4.3.1 Finding all holomorphic products of a given weight

The method `borcherds_input_by_weight(k, prec)` outputs a list of all nearly-holomorphic vector-valued modular forms (to precision `prec`) whose Borcherds lifts are holomorphic and have weight `k`.

Example. To find the two Siegel modular forms of degree 2 and weight 35 that are Borcherds products: input

```
ParamodularForms(1).borcherds_input_by_weight(35, 5)
```

which produces the input functions to precision $O(q^5)$.

4.3.2 Bases of holomorphic products

Let $D \in \mathbb{R}_{>0}$ be a bound. The method `borcherds_input_basis(D, prec)` outputs a list (F_1, \dots, F_N) of nearly-holomorphic vector-valued modular forms (to precision `prec`) with a pole at ∞ of order at most D , and which is minimal with the following property: the input functions F with pole order at most D whose Borcherds lifts are holomorphic are exactly the linear combinations

$$F = k_1 F_1 + \dots + k_N F_N, \quad k_i \in \mathbb{N}_0.$$

Example. To compute the semigroup of holomorphic Borcherds products for the paramodular group of level $N = 5$ with zeros on Humbert surfaces of discriminant at most 10. Input:

```
ParamodularForms(5).borcherds_input_basis(1/2, 5)
```

Taking the Borcherds lifts of these forms yields 13 semigroup generators. These generators have weights 4, 5, 10, 11, 17, 18, 23, 24, 29, 30, 36, 42, 48.

The method `borcherds_input_Qbasis(D, prec)` is similar, but the list (F_1, \dots, F_N) it outputs is minimal with the following weaker property: every input function F with pole order at most D whose Borcherds lift is holomorphic is a linear combination

$$F = \lambda_1 F_1 + \dots + \lambda_N F_N$$

where $\lambda_i \in \mathbb{Q}_{\geq 0}$. Computing a \mathbb{Q} -basis in this sense is often much faster than computing a true Hilbert basis.

4.4 Other methods

4.4.1 Jacobian

Suppose L has rank n and a list F_0, \dots, F_n of $(n+1)$ orthogonal modular forms of weights k_0, \dots, k_n is given. The function

```
jacobian([F_0, ..., F_n])
```

computes the modular Jacobian, or Rankin–Cohen–Ibukiyama operator:

$$J(F_0, \dots, F_n) = \det \begin{pmatrix} k_0 F_0 & \dots & k_n F_n \\ \nabla F_0 & \dots & \nabla F_n \end{pmatrix}.$$

Example. The Jacobian of the Siegel Eisenstein series E_4, E_6, E_{10}, E_{12} is the Siegel cusp form of weight 35. Check this with

```
m = ParamodularForms(1)
C = -589927441461779261030400000/2354734631251
jacobian([m.eisenstein_series(k, 7) for k in [4, 6, 10, 12]]) / C
```

(We divide at the end to remove the funny multiple from the Fourier coefficients.)

4.4.2 Linear relations

The method `omf_rank(X)` determines the dimension of the space spanned by the list of orthogonal modular forms X . (Warning: we only check the rank using the known coefficients! This does not use any sort of Sturm bound so it cannot prove that a given set of modular forms does not have full rank!)

The method `relations(X)` determines the linear relations satisfied by the list of orthogonal modular forms X . (A similar warning applies here; we only check that the relations hold among all known coefficients.)

Example. We check that the square of the Siegel Eisenstein series of weight 4 equals the Siegel Eisenstein series of weight 8.

```
m = ParamodularForms(1)
e4 = m.eisenstein_series(4, 5)
e8 = m.eisenstein_series(8, 5)
relations([e4 * e4, e8])
```

4.4.3 Maass relations

The method `f.is_lift()` tests whether the given orthogonal modular form f satisfies the Maass relations, i.e. whether it is a lift.

Example. Test whether the Borchers product of weight 9 associated to the Gram matrix $\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$ satisfies the Maass relations:

```
m = OrthogonalModularForms(matrix([[2, 1], [1, 2]]))
X = m.borcherds_input_Qbasis(1/3, 15)[0]
X.borcherds_lift().is_lift()
```

4.4.4 Siegel Phi operator

The Siegel Phi operator is a linear map

$$\Phi : M_k(\Gamma_L) \rightarrow M_k, \quad \Phi f(\tau) := \lim_{w \rightarrow i\infty} f(\tau, 0, w).$$

(In other words Φf is the constant term of f 's Fourier–Jacobi expansion.) This is given by the method `f.phi()`.

Note: the result is implemented as an orthogonal modular form of weight $k/2$ for the Lorentzian lattice \mathbb{Z} with generator of norm -1 (see the next chapter). This corresponds to weight k for $\mathrm{Mp}_2(\mathbb{Z})$.

4.4.5 Witt operator

The Witt operator is a linear map

$$W : M_k(\Gamma_L) \rightarrow M_k(\mathrm{Mp}_2(\mathbb{Z}) \times \mathrm{Mp}_2(\mathbb{Z})), \quad Wf(\tau, w) := f(\tau, 0, w).$$

(In other words we evaluate all terms in f 's Fourier–Jacobi expansion at $\mathfrak{z} = 0$.) This is given by the method `f.witt()`.

Note: the result is implemented as an orthogonal modular form for the Lorentzian lattice \mathbb{Z}^2 with quadratic form $Q(x, y) = x(y - x)$.

5 Modular forms on orthogonal groups II

In this chapter we compute with orthogonal modular forms attached to more general lattices of the form $L + \text{II}_{1,1}(N)$, where $\text{II}_{1,1}(N)$ is the hyperbolic plane rescaled by N (i.e. the plane \mathbb{Z}^2 with quadratic form $(x, y) \mapsto Nxy$) and where L is a Lorentzian lattice i.e. of signature $(l-1, 1)$. Construct an `OrthogonalModularForms` instance as follows:

(1) If $N = 1$, then

```
OrthogonalModularForms(S)
```

where S is a Gram matrix for the Lorentzian part L , or

```
OrthogonalModularForms(w)
```

where w is a `WeilRep` instance for a Lorentzian quadratic form.

(2) For general N , call

```
OrthogonalModularForms(w + II(N))
```

where w is the `WeilRep` for the Lorentzian part L .

Warning: for most applications we need to fix a generator of the negative cone attached to L . The program always tries to choose the vector $(1, 0, \dots, 0)$. In other words *the Gram matrix S must always have a strictly negative upper-left entry*; otherwise many things do not work! (In earlier versions we used the vector $(0, \dots, 0, 1)$ and considered the bottom-right entry!)

5.1 Construction of modular forms

Suppose $m = \text{OrthogonalModularForms}(w)$ is an orthogonal modular forms instance where w is Lorentzian or of the form $w_0 + \text{II}(N)$ where w_0 is Lorentzian.

5.1.1 Eisenstein series

The method

```
m.eisenstein_series(k, prec)
```

computes the Fourier series of the Eisenstein series of weight k to precision $prec$.

5.1.2 Additive theta lifts

The additive theta lift of a modular form f of weight $1 + k - n/2$ is implemented with the method

```
f.theta_lift()
```

The result is an orthogonal modular form of weight k .

A basis of the space of cuspidal theta lifts can be computed using the method

```
m.lifts_basis(k, prec)
```

where k is the desired weight and $prec$ is the precision to which the Fourier series is computed.

5.1.3 Borcherds lift

Suppose f is a nearly-holomorphic modular form of weight $1 - n/2$ with integral Fourier coefficients. The Borcherds product constructed from f is implemented with the method

```
f.borcherds_lift()
```

To compute Hilbert bases of input functions into the Borcherds lift, use the commands

```
m.borcherds_input_basis(pole_order, prec)
```

and

```
m.borcherds_input_Qbasis(pole_order, prec)
```

exactly as in section 4.3.2. (Generally the Qbasis is much faster.) Finding all products of a given weight is not (yet?) implemented.

Example. Suppose $L = \text{II}_{1,1}$. The lift of $j(\tau) - 744$ is the modular function $j(\tau_1) - j(\tau_2)$. To check this, input:

```
j = OrthogonalModularForms(II(1)).borcherds_input_basis(1, 10)[1]
j.borcherds_lift()
```

Example. The lattice $A_1(2) + 2U(2)$ admits 10 products of singular weight 1 (cf. [20]). We can compute them as follows. (Warning: this computation is slow; just under 40 seconds on my computer)

```
w = WeilRep(matrix([[4]]))
m = OrthogonalModularForms(w + II(2) + II(2))
X = m.borcherds_input_basis(1/8, 15)
for x in X:
    print(x.principal_part())
    print(x.borcherds_lift())
    print('-', * 80)
```

This yields the 10 genus two theta constants.

5.2 Other functions

The functions *jacobian()*, *omf_rank()*, *relations()* from section 4 can also be applied to the more general orthogonal modular forms considered here. The Siegel Phi and Witt operators can be applied to orthogonal modular forms for lattices constructed from WeilReps of the form $w + \text{II}(n_1) + \text{II}(n_2)$ with w positive-definite.

5.3 Special modular forms

5.3.1 Hilbert modular forms

Hilbert modular forms for real-quadratic number fields can be identified with certain orthogonal modular forms for subgroups of $\text{O}(2, 2)$.

If K is a real-quadratic number field then $HMF(K)$ represents orthogonal modular forms for the (lorentzian) lattice of integers of K , which are essentially the same as Hilbert modular forms. Modular forms attached to HMF are represented as power series of the form

$$f(\tau_1, \tau_2) = \sum_{\nu} c(\nu) q_1^{\nu} q_2^{\nu'},$$

where $q_n = e^{2\pi i \tau_n}$ and where ν runs through totally-nonnegative elements of the dual lattice $\mathcal{O}_K^{\#}$ i.e. $\nu, \nu' \geq 0$ where ν' is the conjugate. As an example, for Hilbert modular forms over $\mathbb{Q}(\sqrt{5})$:

```
x = var('x')
K.<sqrt5> = NumberField(x^2 - 5)
h = HMF(K)
```

Some congruence subgroups are implemented using

```
h = HMF(K, level)
```

where level is a natural number.

Given a HilbertModularForm f on the full modular group you can compute its character by

```
f.character()
```

Fourier coefficients of f can be extracted using

```
f[a]
```

where $a \in \mathcal{O}_K^\#$ (or more generally in K , for Hilbert modular forms with characters)

The constructions of orthogonal modular forms from section 5 all apply here.

5.3.2 Siegel modular forms and Paramodular forms

For $N \in \mathbb{N}$, *ParamodularForms*(N) represents orthogonal modular forms on $A_1(N) + \text{II}_{2,2}$. These have an interpretation as paramodular forms.

These are represented as orthogonal modular forms in the usual sense. The only extra feature is that their coefficients of f can be extracted using

```
f[A]
```

where, if f has trivial character then A is a symmetric half-integral matrix i.e. it has integral diagonal and half-integral off-diagonal entries. (If f has a character then the exponents A may be more general.)

5.3.3 Hermitian modular forms

Hermitian modular forms of degree two can be identified with certain orthogonal modular forms for subgroups of $\text{O}(4, 2)$.

Suppose K is an imaginary-quadratic number field. *HermitianModularForms*(K) represents orthogonal modular forms for the (positive-definite) lattice of integers \mathcal{O}_K of K . More generally

```
HermitianModularForms(K, level = N)
```

represents orthogonal modular forms for the lattice $\mathcal{O}_K \oplus U(N) \oplus U$ where $U = \text{II}_{1,1}$. These are represented as power series of the form

$$f\left(\begin{pmatrix} \tau & z_1 \\ z_2 & w \end{pmatrix}\right) = \sum_A c(A) q^a r_1^b r_2^{\bar{b}} s^c,$$

where $q = e^{2\pi i \tau}$, $r_i = e^{2\pi i z_i}$, $s = e^{2\pi i w}$, and where

$$A = \begin{pmatrix} a & b \\ \bar{b} & c \end{pmatrix}$$

runs through Hermitian half-integral matrices with values in K . The Fourier coefficients of f can be extracted with

```
f[A]
```

where A is a matrix.

6 Algebraic modular forms

Let L be a positive-definite even integral lattice, and let

$$\text{gen}(L) = \{L_1, \dots, L_h\}$$

be the genus of L . So L_1, \dots, L_h are lattices that are equivalent after changing scalars to \mathbb{R} or the p -adic integers \mathbb{Z}_p , but they are not equivalent over \mathbb{Z} .

Let $k \in \mathbb{N}_0$. For a lattice M , let $H_k(M)$ be the space of harmonic polynomials of degree k ; that is, homogeneous polynomials of degree k on $M \otimes \mathbb{C}$ that are annihilated by the Laplace operator

$$\Delta_i = \frac{1}{2} \sum_{i,j=1}^n s^{ij} \frac{\partial^2}{\partial x_i \partial x_j},$$

where we choose any coordinates x_1, \dots, x_n on $M \otimes \mathbb{C}$, let $S = (s_{ij})$ be the Gram matrix of M in those coordinates, and write $S^{-1} = (s^{ij})$.

An **algebraic modular form** of weight k on the orthogonal group $O(L)$ is a sequence $(p_i)_{i=1}^h$ indexed by the genus $\text{gen}(L)$, where each p_i belongs to $H_k(L_i)$ and is invariant under the action of $O(L_i)$ via

$$\gamma \cdot p_i(x) = p_i(\gamma x).$$

More generally one can define modular forms weighted by any representation of $O(n)$. We only consider the irreducible representations of $O(n)$ on harmonic polynomials and their twists by spinor characters (see [21]) and the determinant. For any squarefree divisor d of the level of L , let ν_d be the character of \mathbb{Q}^\times defined on primes p by

$$\nu_d(p) = \begin{cases} -1 & : p|d; \\ 1 & : p \nmid d. \end{cases}$$

Then let

$$\text{spin}_d(\gamma) := \nu_d(N(\gamma)), \quad \gamma \in O(L),$$

where $N(\gamma) \in \mathbb{Q}^\times / (\mathbb{Q}^\times)^2$ is the spinor norm.

6.1 Construction

An *AlgebraicModularForms* instance is constructed with

```
AlgebraicModularForms(S)
```

where S is (1) a positive-definite symmetric integer matrix whose diagonal consists of even integers; or (2) a positive-definite QuadraticForm defined over the integers; or (3) a positive-definite WeilRep.

6.2 Algebraic modular forms

Suppose

```
m = AlgebraicModularForms(S)
```

is an *AlgebraicModularForms* instance.

6.2.1 Basis

To construct a basis of algebraic modular forms of weight k , use the method

`m.basis(k)`

Note that we do not compute a basis by direct linear algebra. Instead we first compute the dimension $\dim M_k$, iterate over monomials of degree k , and turn them successively into algebraic modular forms via harmonic projection until we have found enough to span the space. (This usually seems to be faster.)

Example. The genus of positive-definite lattices of rank 4 and discriminant 29 contains two \mathbb{Z} -equivalence classes, represented by the Gram matrices

$$S_1 = \begin{pmatrix} 2 & -1 & 0 & -1 \\ -1 & 2 & 0 & 1 \\ 0 & 0 & 2 & -1 \\ -1 & 1 & -1 & 6 \end{pmatrix}, \quad S_2 = \begin{pmatrix} 2 & -1 & 1 & 1 \\ -1 & 2 & -1 & 0 \\ 1 & -1 & 2 & 0 \\ 1 & 0 & 0 & 8 \end{pmatrix}.$$

The space of modular forms of weight two is three-dimensional, corresponding to two quadratic invariant harmonic polynomials for S_1 and one for S_2 . Using the command

`X = AlgebraicModularForms(S1).basis(2)`

and inspecting its elements, we obtain the bases

$$2(-x_0^2 + x_0x_1 - x_1^2 + x_0x_3 - x_1x_3) + 9x_3^2,$$

$$13(x_0^2 - x_0x_1 + x_1^2 - x_0x_3 + x_1x_3) + 27(-x_2^2 + x_2x_3)$$

for S_1 and

$$2(-x_0^2 + x_0x_1 - x_1^2 - x_0x_2 + x_1x_2 - x_2^2 - x_0x_3) + 21x_3^2$$

for S_2 . (Note that the basis of harmonic invariant polynomials for S_1 is not as simple as it could be!)

6.2.2 Dimension

To compute the dimension of the space of algebraic modular forms of weight k , use the method

`m.dimension(k)`

6.2.3 Eisenstein series

The **Eisenstein series** is the modular form of weight 0 that assigns the constant 1 to every class $L_i \in \text{gen}(L)$. It is implemented with

`m.eisenstein_series()`

(Note that the Eisenstein series does not take a weight as argument.)

6.3 Hecke operators

Let p be a prime and $d \in \mathbb{N}$, and let L be a lattice with $p \nmid \det(L)$. A p^d -neighbor of L is a lattice $M \subseteq L \otimes \mathbb{Q}$ with the property

$$L/(L \cap M) \cong M/(L \cap M) \cong (\mathbb{Z}/p\mathbb{Z})^d.$$

The **Hecke operator** $T_{p,d}$ of index p and degree d is defined as follows. Suppose L_1, \dots, L_h represent $\text{gen}(L)$. For an algebraic modular form

$$f = (p_i)_{i=1}^h$$

of weight k , where each $p_i \in H_k(L_i)$, define

$$T_{p,d}f = (q_i)_{i=1}^h,$$

where

$$q_i = \sum_{p^k\text{-neighbors } M} p_j(B_M A_M x),$$

where A_M is a change-of-basis map (defined over $\mathbb{Z}[1/p]$) from L to $L \cap M$ and where B_M is an isometry (defined over \mathbb{Z}) from M to some L_j .

If L has rank n then the Hecke operators $T_{p,d}$ of degrees $d \leq \lfloor n/2 \rfloor$ generate the local Hecke algebra \mathcal{H}_p . When n is even, the operator $T_{p, \lfloor n/2 \rfloor}$ only appears when $O(L)$ splits over \mathbb{Q}_p .

The computation of p^d -neighbors uses the algorithms described in Chapter 5 of Hein's thesis [16].

6.3.1 Construction

Suppose m is an `AlgebraicModularForms` instance. To construct the Hecke operator $T_{p,d}$ of index p and degree d , use the command

```
T = m.hecke_operator(p, d)
```

If d is not given then it is assumed to be 1; so the following command will construct $T_{p,1}$:

```
T = m.hecke_operator(p)
```

6.3.2 Action

Let $T = T_{p,d}$ be a Hecke operator. If f is an algebraic modular form then the image $f|T$ is computed using

```
T(f)
```

To get the matrix of $T = T_{p,d}$ with respect to a basis X of algebraic modular forms, use the command

```
T.matrix(X)
```

6.4 Eigenforms

Usually, the command

```
X = m.eigenforms(k)
```

will produce a set X of simultaneous eigenforms of the Hecke operators.

Warning: the set X that results is not generally a basis! It will contain a single representative of each Galois orbit of eigenforms.

We do this by successively computing the eigenspaces under the Hecke operators $T_{p,1}$ at primes $p \nmid \det(L)$ until the space of modular forms breaks up into one-dimensional eigenspaces. In most cases, a single operator $T_{p,1}$ is enough.

Warning: it can sometimes happen that eigenforms cannot be distinguished by their eigenvalues at good primes; i.e. multiplicity one might fail. One example where this problem apparently occurs is described in Section 6.4.1 of Murphy's thesis [19]. This problem might be due to the presence of oldforms and should not occur for maximal lattices; see also Remark 3.2 of [2].

The method *eigenforms* produces instances of a class *AlgebraicModularFormEigenform*, which have a few additional methods. Suppose f is an *AlgebraicModularFormEigenform*.

6.4.1 Field

The method

`f.field()`

returns the field generated by the Hecke eigenvalues of f . (This is also the field over which the coefficients of the polynomials making up f are defined.)

6.4.2 Eigenvalue

The method

`f.eigenvalue(p, d)`

computes the eigenvalue of f under the Hecke operator $T_{p,d}$. (If d is not given then we assume $d = 1$.)

The algorithm works by sampling the polynomials that make up f and $T_{p,d}(f)$ at random rational values (with bounded denominator). In theory this could fail to compute the eigenvalue, but it is unlikely.

7 Modular forms on complex balls

There are a few tools implemented to study modular forms on unitary groups $U(n, 1)$ acting on Hermitian lattices over an imaginary-quadratic field K . I hope to expand on this later.

We will mostly follow the setup of [17]. Let K be an imaginary-quadratic field, with ring of integers \mathcal{O}_K and discriminant d_K .

Note. These are not the Hermitian modular forms in the sense of Braun which are also related to unitary groups; specifically the lattice \mathcal{O}_K^{2n} with the block Gram matrix $\begin{pmatrix} 0 & -iI \\ iI & 0 \end{pmatrix}$, where I is the $(n \times n)$ identity matrix. The case $n = 2$ of that is discussed above.

7.1 Weil representations associated to Hermitian lattices

An even integral Hermitian lattice is a free \mathcal{O}_K -module L , together with a nondegenerate integral Hermitian form $\langle -, - \rangle$, which we understand to be linear in the first argument and conjugate-linear in the second i.e.

$$\langle \lambda x, \mu y \rangle = \lambda \bar{\mu} \langle x, y \rangle, \quad \lambda, \mu \in \mathcal{O}_K, \quad x, y \in L,$$

and which satisfies

$$\langle x, y \rangle, \frac{\langle x, x \rangle}{2} \in d_K^{-1/2} \mathcal{O}_K \text{ for all } x, y \in L.$$

The form $H(x) := \langle x, x \rangle / 2$ is

If we write $\langle x, x \rangle = 2d_K^{-1/2}(a + b(d_K + \sqrt{d_K})/2)$ with $a, b \in \mathbb{Z}$ then we obtain

$$\langle x, x \rangle = \frac{1}{2} \text{Tr}_{K/\mathbb{Q}} \langle x, x \rangle = b \in \mathbb{Z}.$$

The *dual lattice* to L is

$$L' = \{x \in L \otimes_{\mathcal{O}_K} K : \langle x, y \rangle \in d_K^{-1/2} \mathcal{O}_K \text{ for all } y \in L\}.$$

The quotient L'/L is a finite \mathcal{O}_K -module called the *discriminant* of L .

For any even integral Hermitian lattice L , we define an even lattice over \mathbb{Z} with underlying group L and quadratic form

$$Q(x) := \text{Tr}_{K/\mathbb{Q}}\langle x, x \rangle / 2.$$

There is an isomorphism of abelian groups

$$L'/L \xrightarrow{\sim} L'_{\mathbb{Z}}/L_{\mathbb{Z}}, \quad x + L \mapsto x + L_{\mathbb{Z}}.$$

The *Weil representation* associated to the pair $(L, \langle -, - \rangle)$ is just the Weil representation associated to $L_{\mathbb{Z}}$.

To construct the Weil representation attached to a Hermitian lattice, enter

```
WeilRep(S, gen = None)
```

where S is a Hermitian matrix with entries in K (meant to represent the Gram matrix of L with respect to some basis), and where gen is (optionally) a generator for \mathcal{O}_K over \mathbb{Z} . By default we take gen to be $(d_K + \sqrt{d_K})/2$.

Examples.

(i) Over $K = \mathbb{Q}(\sqrt{-3})$, the Weil representation associated to the Hermitian lattice $\mathcal{O}_K = \mathbb{Z}[\zeta_6]$ (with generator $\zeta_6 = e^{\pi i/3}$) with Hermitian form $H(x) = |x|^2/2$ can be constructed with

```
K.<isqrt3> = QuadraticField(-3)
w = WeilRep(matrix(K, [[1]]), gen = (1 + isqrt3) / 2)
```

(ii) The *hyperbolic plane* in the context of Hermitian lattices is the lattice $H = \mathcal{O}_K^2$ with Hermitian form given by the Gram matrix $\begin{pmatrix} 0 & -1/\sqrt{d_K} \\ 1/\sqrt{d_K} & 0 \end{pmatrix}$. In particular $H_{\mathbb{Z}}$ is the unimodular lattice of signature $(2, 2)$.

7.1.1 Gram matrix

To extract the Hermitian Gram matrix from the Weil representation w attached to a Hermitian lattice, use

```
w.complex_gram_matrix()
```

Note: the method

```
w.gram_matrix()
```

instead produces the Gram matrix of the underlying \mathbb{Z} -lattice.

7.1.2 Reflections

Let $\alpha \in \mathcal{O}_K^\times$ be a unit, $\alpha \neq 1$. For certain vectors $r \in L'$ the *reflection*

$$\sigma_{r,\alpha} : v \mapsto v - (1 - \alpha) \frac{\langle r, v \rangle}{\langle r, r \rangle} r$$

preserves the lattice L and induces an automorphism of the discriminant form L'/L . This automorphism can be constructed with the method

```
w.unitary_reflection(r, alpha)
```

7.2 Borchers products on unitary groups

Given a WeilRep instance w associated to a Hermitian lattice of signature $(n, 1)$, the ring of unitary modular forms is created with

```
UnitaryModularForms(w)
```

Note: currently this only accepts w of the form $w_0 + \Pi(N)$ with positive-definite w_0 and $N \in \mathcal{O}_K^\#$.

Similarly to the case of orthogonal groups (cf. 4.3), to compute a Hilbert basis of those nearly-holomorphic vector-valued modular forms to precision $prec$, with pole at ∞ of order at most D whose Borchers lift restricts to a holomorphic modular form on $U(n, 1)$, use the command

```
UnitaryModularForms(w).borcherds_input_basis(D, prec)
```

To produce a list of modular forms whose Borchers lifts (to $U(n, 1)$) are holomorphic and whose \mathbb{Q} -span contains all forms in the Hilbert basis, use

```
UnitaryModularForms(w).borcherds_input_Qbasis(D, prec)
```

This is usually faster.

Example. To compute Borchers products with pole order at most 1 for the $\mathbb{Z}[e^{2\pi i/3}]$ -lattice with Gram matrix $\text{diag}(1, 1, -1)$, or equivalently the Gram matrix $\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$, enter:

```
K.<isqrt3> = QuadraticField(-3)
w = WeilRep(matrix(K, [1]), gen = (-1 + isqrt3) / 2) + II(isqrt3)
X = UnitaryModularForms(w).borcherds_input_Qbasis(1, 10)
```

8 Paramodular forms

8.1 Introduction

Paramodular forms (of degree two) of level N are Siegel modular forms which transform under the group

$$K(N) = \left\{ M \in \text{Sp}_4(\mathbb{Q}) : M \in \begin{pmatrix} \mathbb{Z} & \mathbb{Z} & \frac{1}{N}\mathbb{Z} & \mathbb{Z} \\ N\mathbb{Z} & \mathbb{Z} & \mathbb{Z} & \mathbb{Z} \\ N\mathbb{Z} & N\mathbb{Z} & \mathbb{Z} & N\mathbb{Z} \\ N\mathbb{Z} & \mathbb{Z} & \mathbb{Z} & \mathbb{Z} \end{pmatrix} \right\}.$$

They are invariant under translations by matrices of the form $\begin{pmatrix} b_1/N & b_2 \\ b_2 & b_3 \end{pmatrix}$ with $b_1, b_2, b_3 \in \mathbb{Z}$ and therefore have a Fourier expansion

$$F\left(\begin{pmatrix} \tau & z \\ z & w \end{pmatrix}\right) = \sum_{a,b,c \in \mathbb{Z}} \alpha_F(a, b, c) q^{Na} r^b s^c, \quad q = e^{2\pi i \tau}, r = e^{2\pi i z}, s = e^{2\pi i w}.$$

They can be interpreted as orthogonal modular forms with respect to the lattice $2U \oplus A_1(N)$. More specifically, if

$$F\left(\begin{pmatrix} \tau & z \\ z & w \end{pmatrix}\right) = \sum_{a,b,c \in \mathbb{Z}} \alpha_F(a, b, c) q^{Na} r^b s^c$$

is the Fourier series of a paramodular form then

$$\sum_{a,b,c} \alpha_F(a, b, c) q^a r^b s^c$$

is the Fourier (or Fourier–Jacobi) expansion of an orthogonal modular form for the discriminant kernel of $2U \oplus A_1(N)$ and vice-versa.

8.2 Construction

Let $N \in \mathbb{N}$.

```
p = ParamodularForms(N)
```

constructs a *ParamodularForms* instance, representing paramodular forms of degree two and level N .

Suppose f is a paramodular form. For a matrix $A = \begin{pmatrix} Na & b/2 \\ b/2 & c \end{pmatrix}$, the coefficient $\alpha_F(a, b, c)$ of $q^{Na}r^bs^c = e^{2\pi i \text{tr}(AZ)}$ is obtained with

```
f[A]
```

The following modular forms can be constructed directly:

8.2.1 Eisenstein series

The paramodular Eisenstein series of even weight $k \geq 4$ can be constructed with

```
p.eisenstein_series(k, prec)
```

Here, *prec* is the precision to which we compute the Fourier series.

8.2.2 Maass space

A basis of the Maass Spezialschar (i.e. the span of all Saito–Kurokawa lifts) can be constructed with

```
p.maass_space(k, prec, cusp_forms = True)
```

If the optional parameter *cusp_forms* is set to False, then we include non-cusp forms in the Maass space.

8.3 Hecke operators

Let p be a prime not dividing the level N . The local Hecke algebra is generated by the double coset operators

$$T_{p,1} = K(N) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} K(N), \quad T_{p,2} = K(N) \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p^2 & 0 \\ 0 & 0 & 0 & p \end{pmatrix}.$$

To construct the Hecke operator $T_{p,d}$, use the command

```
T = p.hecke_operator(p, d = 1)
```

(If d is not given then we assume $d = 1$.)

9 Hermitian modular forms

9.1 Introduction

Let $K = \mathbb{Q}(\sqrt{-D})$ be an imaginary-quadratic field where $-D$ is a fundamental discriminant. Let $n \in \mathbb{N}$ and let \mathbf{H}_n be the space of all complex $(n \times n)$ matrices Z with the property that, in the Hermitian decomposition

$$Z = X + iY, \quad \text{where } X = \overline{X^T} \text{ and } Y = \overline{Y^T},$$

the matrix Y is positive-definite. Let $\Gamma \leq \mathrm{GL}_{2n}(\mathcal{O}_K)$ be a subgroup that satisfies

$$\overline{X^T} J X = J \quad \text{for all } X \in \Gamma, \quad \text{where } J = \begin{pmatrix} 0 & -I \\ I & 0 \end{pmatrix}.$$

(In other words, $\Gamma \leq \mathrm{U}(n, n)$, the unitary group of iJ .) A **Hermitian modular form** of degree n and weight k is a holomorphic function

$$F : \mathbf{H}_n \longrightarrow \mathbb{C}$$

that satisfies

$$F\left((AZ + B)(CZ + D)^{-1}\right) = \det(CZ + D)^k \cdot F(Z)$$

for every block matrix

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \in \Gamma.$$

For $n = 2$, Hermitian modular forms for $\Gamma = \mathrm{U}(2, 2; \mathcal{O}_K)$ are closely related to (orthogonal) modular forms for the signature $(4, 2)$ lattice $U \oplus U \oplus \mathcal{O}_K$, see e.g. [11].

9.2 Construction

Let $K = \mathbb{Q}(\sqrt{-D})$ be an imaginary-quadratic field.

`h = HermitianModularForms(K)`

constructs a *HermitianModularForms* instance, representing Hermitian modular forms of degree two for the group $\mathrm{U}(2, 2; \mathcal{O}_K)$.

A Hermitian modular form is represented as a power series

$$f\left(\begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix}\right) = \sum_A \alpha_f(A) q^a r_1^b r_2^{\bar{b}} s^c,$$

where $q = e^{2\pi i z_{11}}$, $r_1 = e^{2\pi i z_{12}}$, $r_2 = e^{2\pi i z_{21}}$ and $s = e^{2\pi i z_{22}}$, and where

$$A = \begin{pmatrix} a & b \\ \bar{b} & c \end{pmatrix}$$

runs through matrices with $a, c \in \mathbb{Z}$ and $b \in \mathcal{O}_K^\#$. For a *HermitianModularForm* f and a matrix A as above, the coefficient $\alpha_f(A)$ is obtained with

`f[A]`

The following modular forms can be constructed directly:

9.2.1 Eisenstein series

The Hermitian Eisenstein series of even weight $k \geq 4$ can be constructed with

`h.eisenstein_series(k, prec)`

Here, *prec* is the precision to which we compute the Fourier series.

9.2.2 Maass space

A basis of the Sugano Maass space of integer weight k can be constructed with

`h.maass_space(k, prec, cusp_forms = True)`

If the optional parameter *cusp_forms* is set to `False`, then we include non-cusp forms in the Maass space.

9.3 Hecke operators

Let p be a prime. If p remains inert in K , then the local Hecke algebra over p is generated by the double coset operators

$$T_p = \Gamma_K \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \Gamma_K \quad \text{and} \quad T_{p^2} = \Gamma_K \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p^2 & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \Gamma_K,$$

together with the trivial operator $\Delta_p = \Gamma_K \text{diag}(p, p, p, p) \Gamma_K$.

If p splits in K into principal ideals, $p = \pi \bar{\pi}$, then the local Hecke algebra over p is generated by the double coset operators

$$T_\pi = \Gamma_K \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \pi & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & \pi \end{pmatrix} \Gamma_K \quad \text{and} \quad T_{\bar{\pi}} = \Gamma_K \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \bar{\pi} & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & \bar{\pi} \end{pmatrix} \Gamma_K \quad \text{and} \quad T_p = \Gamma_K \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \Gamma_K,$$

together with the trivial operators Δ_π and $\Delta_{\bar{\pi}}$. (If p splits into non-principal ideals then it is more natural to work over the adeles.)

9.3.1 Hecke operators

To construct the Hecke operator T_π , T_p or T_{p^2} , use

`h.hecke_operator(N)`

where $N \in \{\pi, p, p^2\}$.

To apply the Hecke operator T to a Hermitian modular form f , simply write $T(f)$. Note that the precision of the Fourier series of $T(f)$ may be much lower than that of f itself.

9.3.2 Eigenforms

Let X be a basis of a space of Hermitian modular forms that is invariant under the Hecke operators. The method

`h.eigenforms(X)`

will produce a set of Galois representatives of the eigenforms contained in $\text{span}(X)$. (This will fail if X is not linearly independent, or if not enough Fourier coefficients are known.)

Example. For $K = \mathbb{Q}(\sqrt{-3})$, the space $M_{12}(\Gamma_K)$ is spanned by the three series E_4^3 , E_6^2 and E_{12} . To compute the eigenforms, use

```
K.<isqrt3> = QuadraticField(-3)
h = HermitianModularForms(K)
e4, e6, e12 = [h.eisenstein_series(k, 6) for k in [4, 6, 12]]
L = h.eigenforms(e4^3, e6^2, e12)
```

The output consists of the Eisenstein series, the Maass cusp form, and the Klingen Eisenstein series.

9.3.3 Eigenvalues and L -functions

The output of

`h.eigenforms(X)`

consists of HermitianEigenform instances f , which have the following additional methods:

`f.hecke_field()`

returns the number field generated by the eigenvalues of f (equivalently, the field generated by its Fourier coefficients).

`f.eigenvalue(N)`

returns the eigenvalue of f under the Hecke operator T_N , $N \in \{\pi, p, p^2\}$.

`f.euler_factor(p)`

returns the Euler factor $L_p(X)$ in the (degree six) alternating square L -function [14] attached to f ; i.e. such that

$$L^{\wedge 2}(f; s) = \prod_p L_p(p^{-s}).$$

(The eigenvalues and Euler factors at ramified primes are not implemented.)

References

- [1] Ali Ajouz. Hecke operators on Jacobi forms of lattice index and the relation to elliptic modular forms. Dissertation (adviser N. Skoruppa), 2015.
- [2] Eran Assaf, Dan Fretwell, Colin Ingalls, Adam Logan, Spencer Secord, and John Voight. Definite orthogonal modular forms: computations, excursions, and discoveries. *Res. Number Theory*, 8(4):Paper No. 70, 32, 2022. ISSN 2522-0160.
- [3] Richard Borcherds. Automorphic forms with singularities on Grassmannians. *Invent. Math.*, 132(3):491–562, 1998.
- [4] Richard Borcherds. The Gross-Kohnen-Zagier theorem in higher dimensions. *Duke Math. J.*, 97(2):219–233, 1999.
- [5] Vincent Bouchard, Thomas Creutzig, and Aniket Joshi. Hecke operators on vector-valued modular forms. *SIGMA Symmetry Integrability Geom. Methods Appl.*, 15:Paper 041, 31, 2019.
- [6] Kathrin Bringmann, Amanda Folsom, Ken Ono, and Larry Rolen. *Harmonic Maass forms and mock modular forms: theory and applications*, volume 64 of *American Mathematical Society Colloquium Publications*. American Mathematical Society, Providence, Rhode Island, 2017.
- [7] Jan Bruinier. *Borcherds products on $O(2, l)$ and Chern classes of Heegner divisors*, volume 1780 of *Lecture Notes in Mathematics*. Springer-Verlag, Berlin, 2002.
- [8] Jan Bruinier and Michael Bundschuh. On Borcherds products associated with lattices of prime discriminant. *Ramanujan J.*, 7(1-3):49–61, 2003.
- [9] Jan Bruinier and Michael Kuss. Eisenstein series attached to lattices and modular forms on orthogonal groups. *Manuscripta Math.*, 106(4):443–459, 2001.

- [10] Raameon Cowan, Daniel Katz, and Lauren White. A new generating function for calculating the Igusa local zeta function. *Adv. Math.*, 304:355–420, 2017.
- [11] Tobias Dern. Hermitesche Modulformen zweiten Grades. Dissertation (advisers A. Krieg, N.-P. Skoruppa), RWTH Aachen, 2001. URL http://publications.rwth-aachen.de/record/95377/files/Dern_Tobias.pdf.
- [12] Stephan Ehlen and Nils-Peter Skoruppa. Computing invariants of the Weil representation. In *L-functions and automorphic forms*, volume 10 of *Contrib. Math. Comput. Sci.*, pages 81–96. Springer, Cham, 2017.
- [13] Martin Eichler and Don Zagier. *The theory of Jacobi forms*, volume 55 of *Progress in Mathematics*. Birkhäuser Boston, Inc., Boston, MA, 1985.
- [14] V. A. Gritsenko. The zeta function of degree six for Hermitian modular forms of genus 2. *Zap. Nauchn. Sem. Leningrad. Otdel. Mat. Inst. Steklov. (LOMI)*, 154(Anal. Teor. Chisel i Teor. Funktsii. 7):46–66, 176–177, 1986.
- [15] Valery Gritsenko, Nils-Peter Skoruppa, and Don Zagier. Theta blocks. URL <https://arxiv.org/pdf/1907.00188.pdf>.
- [16] Jeffery Hein. Orthogonal modular forms: an application to a conjecture of Birch, algorithms and computations. Dissertation, Dartmouth College, 2016.
- [17] Eric Hofmann. Borchers products on unitary groups. *Math. Ann.*, 358(3-4):799–832, 2014.
- [18] David Lowry-Duda. Visualizing modular forms. URL <https://arxiv.org/pdf/2002.05234>.
- [19] Daniel Kim Murphy. Algebraic modular forms on definite orthogonal groups. Dissertation, Stanford University, 2013.
- [20] Sebastian Opitz and Markus Schwagenscheidt. Holomorphic Borchers products of singular weight for simple lattices of arbitrary level. *Proc. Amer. Math. Soc.*, 147(11):4639–4653, 2019.
- [21] Gustavo Rama and Gonzalo Tornaría. Computation of paramodular forms. In *ANTS XIV—Proceedings of the Fourteenth Algorithmic Number Theory Symposium*, volume 4 of *Open Book Ser.*, pages 353–370. Math. Sci. Publ., Berkeley, CA, 2020.
- [22] Martin Raum. Computing genus 1 Jacobi forms. *Math. Comp.*, 85(298):931–960, 2016.
- [23] Markus Schwagenscheidt. Eisenstein series for the Weil representation. *J. Number Theory*, 193:74–90, 2018.
- [24] Brandon Williams. Poincaré square series for the Weil representation. *Ramanujan J.*, 47(3):605–650, 2018.
- [25] Brandon Williams. Vector-valued Eisenstein series of small weight. *Int. J. Number Theory*, 15(2):265–287, 2019.
- [26] Brandon Williams. A construction of antisymmetric modular forms for Weil representations. *Math. Z.*, 296:391–408, 2020.
- [27] Brandon Williams. Higher pullbacks of modular forms on orthogonal groups. *Forum Math.*, 33(3):631–652, 2021.
- [28] Don Zagier. Traces of singular moduli. In *Motives, polylogarithms and Hodge theory, Part I (Irvine, CA, 1998)*, volume 3 of *Int. Press Lect. Ser.*, pages 211–244. Int. Press, Somerville, MA, 2002.
- [29] Don Zagier. Elliptic modular forms and their applications. In *The 1-2-3 of modular forms*, Universitext, pages 1–103. Springer, Berlin, 2008.