

# SL2Reps

## Constructing symmetric representations of $SL(2, \mathbb{Z})$ .

### 1.1

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# Chapter 1

## Introduction

This package, `SL2Reps`, provides methods for constructing and testing matrix presentations of the representations of  $\mathrm{SL}_2(\mathbb{Z})$  whose kernels are congruence subgroups of  $\mathrm{SL}_2(\mathbb{Z})$ .

Irreducible representations of prime-power level are constructed individually by using the Weil representations of quadratic modules, and from these a list of all representations of a given degree or level can be produced. Each representation is represented by a pair  $(S, T)$ , where  $S$  is a symmetric, unitary matrix and  $T$  is a diagonal matrix of finite order; this format is designed for the study of modular tensor categories in particular.

### 1.1 Installation

To install `SL2Reps`, first download it from <https://snw-0.github.io/sl2-reps/>, then place it in the `pkg` subdirectory of your GAP installation (or in the `pkg` subdirectory of any other GAP root directory, for example one added with the `-1` argument).

`SL2Reps` is then loaded with the GAP command

```
gap> LoadPackage( "SL2Reps" );
```

### 1.2 Usage

Specific irreducible representations may be constructed via the methods in Chapter 3, while lists of irreducible representations with a given degree or level may be constructed with those in Chapter 4.

This package uses an `InfoClass`, `InfoSL2Reps`. It may be set to 0 (silent), 1 (info), or 2 (verbose). To change it, use

```
gap> SetInfoLevel( InfoSL2Reps, k );
```

## Chapter 2

# Description

The group  $\mathrm{SL}_2(\mathbb{Z})$  is generated by  $\mathfrak{s} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$  and  $\mathfrak{t} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$  (which satisfy the relations  $\mathfrak{s}^4 = (\mathfrak{st})^3 = \mathrm{id}$ ). Thus, any complex representation  $\rho$  of  $\mathrm{SL}_2(\mathbb{Z})$  on  $\mathbb{C}^n$  (where  $n \in \mathbb{Z}^+$  is called the *degree* or *dimension* of  $\rho$ ) is determined by the  $n \times n$  matrices  $S = \rho(\mathfrak{s})$  and  $T = \rho(\mathfrak{t})$ .

This package constructs irreducible representations of  $\mathrm{SL}_2(\mathbb{Z})$  which factor through  $\mathrm{SL}_2(\mathbb{Z}/\ell\mathbb{Z})$  for some  $\ell \in \mathbb{Z}^+$ ; the smallest such  $\ell$  is called the *level* of the representation, and is equal to the order of  $T$ . One may equivalently say that the kernel of the representation is a congruence subgroup. Such representations are called *congruent* representations. A congruent representation  $\rho$  is called *symmetric* if  $S = \rho(\mathfrak{s})$  is a symmetric, unitary matrix and  $T = \rho(\mathfrak{t})$  is a diagonal matrix; it was proved by the authors that every congruent representation is equivalent to a symmetric one (see 2.1.4). Any representation of  $\mathrm{SL}_2(\mathbb{Z})$  arising from a modular tensor category is symmetric [DLN15].

We therefore present representations in the form of a record `rec(S, T, degree, level, name)`, where the name follows the conventions of [NW76].

Note that our definition of  $\mathfrak{s}$  follows that of [Nob76]; other authors prefer the inverse, i.e.  $\mathfrak{s} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$  (under which convention the relations are  $\mathfrak{s}^4 = \mathrm{id}$ ,  $(\mathfrak{st})^3 = \mathfrak{s}^2$ ). When working with that convention, one must invert the  $S$  matrices output by this package.

Throughout, we denote by  $\mathbf{e}$  the map  $k \mapsto e^{2\pi i k}$  (an isomorphism from  $\mathbb{Q}/\mathbb{Z}$  to the group of finite roots of unity in  $\mathbb{C}$ ). For a group  $G$ , we denote by  $\widehat{G}$  the character group  $\mathrm{Hom}(G, \mathbb{C}^\times)$ .

### 2.1 Construction

Any representation  $\rho$  of  $\mathrm{SL}_2(\mathbb{Z})$  can be decomposed into a direct sum of irreducible representations (irreps). Further, if  $\rho$  has finite level, each irrep can be factorized into a tensor product of irreps whose levels are powers of distinct primes (using the Chinese remainder theorem). Therefore, to characterize all finite-dimensional representations of  $\mathrm{SL}_2(\mathbb{Z})$  of finite level, it suffices to consider irreps of  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$  for primes  $p$  and positive integers  $\lambda$ .

#### 2.1.1 Weil representations

Such representations may be constructed using Weil representations as described in [Nob76, Section 1]. We give a brief summary of the process here. First, if  $M$  is any additive abelian group, a *quadratic form* on  $M$  is a map  $Q : M \rightarrow \mathbb{Q}/\mathbb{Z}$  such that

- $Q(-x) = Q(x)$  for all  $x \in M$ , and

- $B(x, y) = Q(x + y) - Q(x) - Q(y)$  defines a  $\mathbb{Z}$ -bilinear map  $M \times M \rightarrow \mathbb{Q}/\mathbb{Z}$ .

Now let  $p$  be a prime number and  $\lambda \in \mathbb{Z}^+$ . Choose a  $\mathbb{Z}/p^\lambda\mathbb{Z}$ -module  $M$  and a quadratic form  $Q$  on  $M$  such that the pair  $(M, Q)$  is of one of the three types described in Section 2.2. Each such  $M$  is a ring, and has at most 2 cyclic factors as an additive group. Those with 2 cyclic factors may be identified with a quotient of the quadratic integers, giving a norm on  $M$ . Then the *quadratic module*  $(M, Q)$  gives rise to a representation of  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$  on the vector space  $V = \mathbb{C}^M$  of complex-valued functions on  $M$ . This representation is denoted  $W(M, Q)$ . Note that the *central charge* of  $(M, Q)$  is given by  $S_Q(-1) = \frac{1}{\sqrt{|M|}} \sum_{x \in M} \mathbf{e}(Q(x))$ .

### 2.1.2 Character subspaces and primitive characters

A family of subrepresentations  $W(M, Q, \chi)$  of  $W(M, Q)$  may be constructed as follows. Denote

$$\mathrm{Aut}(M, Q) = \{\varepsilon \in \mathrm{Aut}(M) \mid Q(\varepsilon x) = Q(x) \text{ for all } x \in M\}.$$

We then associate to  $(M, Q)$  an abelian subgroup  $\mathfrak{A} \leq \mathrm{Aut}(M, Q)$ ; the structure of this group depends on  $(M, Q)$  and is described in Section 2.2. Note that  $\mathfrak{A}$  has at most two cyclic factors, whose generators we denote by  $\alpha$  and  $\beta$ . Now, let  $\chi \in \widehat{\mathfrak{A}}$  be a 1-dimensional representation (*character*) of  $\mathfrak{A}$ , and define

$$V_\chi = \{f \in V \mid f(\varepsilon x) = \chi(\varepsilon)f(x) \text{ for all } x \in M \text{ and } \varepsilon \in \mathfrak{A}\},$$

which is a  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ -invariant subspace of  $V$ . We then denote by  $W(M, Q, \chi)$  the subrepresentation of  $W(M, Q)$  on  $V_\chi$ . Note that  $W(M, Q, \chi) \cong W(M, Q, \bar{\chi})$ .

For the abelian groups  $\mathfrak{A} \leq \mathrm{Aut}(M, Q)$ , we will frequently refer to a character  $\chi \in \widehat{\mathfrak{A}}$  as being *primitive*. With the exception of a single family of modules of type  $R$  (the *extremal* case, for which see Section 2.2.4), primitivity amounts to the following: there exists some  $\varepsilon \in \mathfrak{A}$  such that  $\chi(\varepsilon) \neq 1$  and  $\varepsilon$  fixes the submodule  $pM \subset M$  pointwise. There exists a subgroup  $\mathfrak{A}_0 \leq \mathfrak{A}$  such that a non-trivial  $\chi \in \widehat{\mathfrak{A}}$  is primitive if and only if  $\chi$  is injective on  $\mathfrak{A}_0$  (or, equivalently, if  $\mathfrak{A}_0 \cap \ker \chi$  is trivial).

Explicit descriptions of the group  $\mathfrak{A}_0$  for each type are given in Section 2.2 and may be used to determine the primitive characters.

### 2.1.3 Irrep Types

All irreps of prime-power level and finite degree may then be constructed in one of three ways ([NW76, Hauptsatz 2]):

- The overwhelming majority are of the form  $W(M, Q, \chi)$  for  $\chi$  primitive and  $\chi^2 \neq 1$ ; we call these *standard*. This includes the primitive characters from the extremal case.
- A finite number, and a single infinite family arising from the extremal case (Section 2.2.4), are instead constructed by using non-primitive characters or primitive characters  $\chi$  with  $\chi^2 = 1$ . We call these *non-standard*.
- Finally, 18 *exceptional* irreps are constructed as tensor products of two irreps from the other two cases. A full list of these may be constructed by `SL2IrrepsExceptional` (4.3.1).

### 2.1.4 S and T matrices

The images  $W(M, Q)(s)(f)$  and  $W(M, Q)(t)(f)$  may be calculated for any  $f \in V$  (see [Nob76, Satz 2]). Thus, to construct  $S$  and  $T$  matrices for the irreducible subrepresentations of  $W(M, Q)$ , it suffices to find bases for the  $W(M, Q)$ -invariant subspaces of  $V$ . Choices for such bases are given by [NW76]; however, these often result in non-symmetric  $S$  matrices. It has been proven by the authors of this package that, for all standard and non-standard irreps, there exists a basis for the corresponding subspace of  $V$  such that  $S$  is symmetric and unitary and  $T$  is diagonal ([NWW21], in preparation). In particular,  $S$  is always either a real matrix or  $i$  times a real matrix. It follows that these properties hold for the exceptional irreps as well. This package therefore produces matrices with these properties.

All the finite-dimensional irreducible representations of  $SL_2(\mathbb{Z})$  of finite level can now be constructed by taking tensor products of these prime-power irreps. Note that, if two representations are determined by pairs  $[S1, T1]$  and  $[S2, T2]$ , then the pair for their tensor product may be calculated via the GAP command `KroneckerProduct`, namely as `[KroneckerProduct(S1, S2), KroneckerProduct(T1, T2)]`.

## 2.2 Weil representation types

### 2.2.1 Type D

Let  $p$  be prime. If  $p = 2$  or  $p = 3$ , let  $\lambda \geq 2$ ; otherwise, let  $\lambda \geq 1$ . Then the Weil representation arising from the quadratic module with

$$M = \mathbb{Z}/p^\lambda \mathbb{Z} \oplus \mathbb{Z}/p^\lambda \mathbb{Z} \quad \text{and} \quad Q(x, y) = \frac{xy}{p^\lambda}$$

is said to be of type  $D$  and denoted  $D(p, \lambda)$ . Information on type  $D$  quadratic modules may be obtained via `SL2ModuleD` (3.1.1), and subrepresentations of  $D(p, \lambda)$  with level  $p^\lambda$  may be constructed via `SL2IrrepD` (3.1.2).

The group

$$\mathfrak{A} \cong (\mathbb{Z}/p^\lambda \mathbb{Z})^\times$$

acts on  $M$  by  $a(x, y) = (a^{-1}x, ay)$  and is thus identified with a subgroup of  $\text{Aut}(M, Q)$ ; see [NW76, Section 2.1]. The group  $\mathfrak{A}$  has order  $p^{\lambda-1}(p-1)$  and  $\mathfrak{A} = \langle \alpha \rangle \times \langle \beta \rangle$ . The relevant information for type  $D$  quadratic modules is as follows:

$p$	$\lambda$	$\alpha$	$\beta$	$\mathfrak{A}_0$
$> 2$	1	1	$ \beta  = p-1$	$\langle 1 \rangle$
$> 2$	$> 1$	$ \alpha  = p^{\lambda-1}$ (e.g. $\alpha = 1+p$ )	$ \beta  = p-1$	$\langle \alpha \rangle$
2	2	1	-1	$\langle 1 \rangle$
2	$> 2$	$ \alpha  = 2^{\lambda-2}$ (e.g. $\alpha = 5$ )	-1	$\langle \alpha \rangle$

When  $\mathfrak{A}_0$  is trivial, every non-trivial character  $\chi \in \widehat{\mathfrak{A}}$  is primitive.

### 2.2.2 Type N

Let  $p$  be prime and  $\lambda \geq 1$ . If  $p \neq 2$ , let  $u$  be a positive integer so that  $u \equiv 3 \pmod{4}$  with  $-u$  a quadratic non-residue mod  $p$ ; if  $p = 2$ , let  $u = 3$ . Then the Weil representation arising from the quadratic module with

$$M = \mathbb{Z}/p^\lambda \mathbb{Z} \oplus \mathbb{Z}/p^\lambda \mathbb{Z} \quad \text{and} \quad Q(x, y) = \frac{x^2 + xy + \frac{1+u}{4}y^2}{p^\lambda}$$

is said to be of type  $N$  and denoted  $N(p, \lambda)$ . Information on type  $N$  quadratic modules may be obtained via `SL2ModuleN` (3.2.1), and subrepresentations of  $N(p, \lambda)$  with level  $p^\lambda$  may be constructed via `SL2IrrepN` (3.2.2).

The additive group  $M$  is a ring with multiplication given by

$$(x_1, y_1) \cdot (x_2, y_2) = (x_1 x_2 - \frac{1+u}{4} y_1 y_2, x_1 y_2 + x_2 y_1 + y_1 y_2)$$

and identity element  $(1, 0)$ . We define a norm  $\text{Nm}(x, y) = x^2 + xy + \frac{1+u}{4} y^2$  on  $M$ ; then the multiplicative subgroup

$$\mathfrak{A} = \{\varepsilon \in M^\times \mid \text{Nm}(\varepsilon) = 1\}$$

of  $M^\times$  acts on  $M$  by multiplication and is identified with a subgroup of  $\text{Aut}(M, Q)$ ; see [NW76, Section 2.2].

The group  $\mathfrak{A}$  has order  $p^{\lambda-1}(p+1)$  and  $\mathfrak{A} = \langle \alpha \rangle \times \langle \beta \rangle$ . The relevant information for type  $N$  quadratic modules is as follows:

$p$	$\lambda$	$\alpha$	$\beta$	$\mathfrak{A}_0$
$> 2$	1	$(1, 0)$	$ \beta  = p+1$	$\langle (1, 0) \rangle$
$> 2$	$> 1$	$ \alpha  = p^{\lambda-1}$	$ \beta  = p+1$	$\langle \alpha \rangle$
2	1	$(1, 0)$	$ \beta  = 3$	$\langle (1, 0) \rangle$
2	2	$(1, 0)$	$ \beta  = 6$	$\langle (-1, 0) \rangle$
2	$> 2$	$ \alpha  = p^{\lambda-2}$	$ \beta  = 6$	$\langle \alpha \rangle$

When  $\mathfrak{A}_0$  is trivial, every non-trivial character  $\chi \in \widehat{\mathfrak{A}}$  is primitive.

### 2.2.3 Type R, generic cases

The structure of the quadratic module  $(M, Q)$  of type  $R$  depends upon three additional parameters:  $\sigma$ ,  $r$ , and  $t$ . Details are as follows:

- If  $p$  is odd, let  $\lambda \geq 2$ ,  $\sigma \in \{1, \dots, \lambda\}$ , and  $r, t \in \{1, u\}$  with  $u$  a quadratic non-residue mod  $p$ . Then define

$$M = \mathbb{Z}/p^\lambda \mathbb{Z} \oplus \mathbb{Z}/p^{\lambda-\sigma} \mathbb{Z} \quad \text{and} \quad Q(x, y) = \frac{r(x^2 + p^\sigma t y^2)}{p^\lambda}.$$

When  $\sigma = \lambda$ , the second factor of  $M$  is trivial, and  $(M, Q)$  is said to be in the *unary* family; otherwise, it is called *generic*.

- If  $p = 2$ , let  $\lambda \geq 2$ ,  $\sigma \in \{0, \dots, \lambda - 2\}$  and  $r, t \in \{1, 3, 5, 7\}$ . Then define

$$M = \mathbb{Z}/2^{\lambda-1} \mathbb{Z} \oplus \mathbb{Z}/2^{\lambda-\sigma-1} \mathbb{Z} \quad \text{and} \quad Q(x, y) = \frac{r(x^2 + 2^\sigma t y^2)}{2^\lambda}.$$

When  $\sigma = \lambda - 2$ , the second factor of  $M$  is isomorphic to  $\mathbb{Z}/2\mathbb{Z}$ , and  $(M, Q)$  is said to be in the *extremal* family; otherwise, it is called *generic*.

In all cases, the resulting representation is said to be of type  $R$  and denoted  $R(p, \lambda, \sigma, r, t)$ . The additive group  $M$  admits a ring structure with multiplication

$$(x_1, y_1) \cdot (x_2, y_2) = (x_1 x_2 - p^\sigma t y_1 y_2, x_1 y_2 + x_2 y_1)$$



and identity element  $(1, 0)$ . We define a norm  $\text{Nm}(x, y) = x^2 + xy + p^\sigma ty^2$  on  $M$ .

In this section, we detail generic type  $R$  quadratic modules. Information on the unary and extremal cases is covered in Section 2.2.4.

Let  $(M, Q)$  be a generic type  $R$  quadratic module. Information on  $(M, Q)$  can be obtained via `SL2ModuleR` (3.3.1), and subrepresentations of  $R(p, \lambda, \sigma, r, t)$  with level  $p^\lambda$  may be constructed via `SL2IrrepR` (3.3.2).

The multiplicative subgroup

$$\mathfrak{A} = \{\varepsilon \in M^\times \mid \text{Nm}(\varepsilon) = 1\}$$

of  $M^\times$  acts on  $M$  by multiplication and is identified with a subgroup of  $\text{Aut}(M, Q)$ ; see [NW76, Section 2.3 – 2.4]. The relevant information is as follows:

- If  $p$  is odd,  $\mathfrak{A} = \langle \alpha \rangle \times \langle \beta \rangle$  with order  $2p^{\lambda-\sigma}$ . In this case, for fixed  $p, \lambda, \sigma$ , each pair  $(r, t)$  gives rise to a distinct quadratic module [Nob76, Satz 4]. The following table covers a complete list of representatives of equivalence classes of such modules.

$p$	$\lambda$	$\sigma$	$(r, t)$	$\alpha$	$\beta$	$\mathfrak{A}_0$
3	2	1	$r, t \in \{1, 2\}$	$ \alpha  = 3$	$(-1, 0)$	$\langle \alpha \rangle$
3	$\geq 3$	1	$t = 1, r \in \{1, 2\}$	$ \alpha  = 3^{\lambda-\sigma-1}$	$ \beta  = 6$	$\langle \alpha \rangle$
3	$\geq 3$	1	$t = 2, r \in \{1, 2\}$	$ \alpha  = 3^{\lambda-\sigma}$	$(-1, 0)$	$\langle \alpha \rangle$
3	$\geq 3$	$2, \dots, \lambda - 1$	$r, t \in \{1, 2\}$	$ \alpha  = 3^{\lambda-\sigma}$	$(-1, 0)$	$\langle \alpha \rangle$
$\geq 5$	$\geq 2$	$1, \dots, \lambda - 1$	$r, t \in \{1, u\}$	$ \alpha  = p^{\lambda-\sigma}$	$(-1, 0)$	$\langle \alpha \rangle$

- If  $p = 2$ , then the generic case occurs when  $\lambda \geq 3$  and  $\sigma \in \{0, \dots, \lambda - 3\}$ . Again,  $\mathfrak{A} = \langle \alpha \rangle \times \langle \beta \rangle$ ; the order is  $2^{\lambda-\sigma-k}$  with  $k \in \{0, 1, 2\}$  (as specified below). In this case, for fixed  $p, \lambda, \sigma$ , two pairs  $(r_1, t_1)$  and  $(r_2, t_2)$  may give rise to equivalent quadratic modules [Nob76, Satz 4]. The following table covers a complete list of representatives of equivalence classes of such modules.

$\lambda$	$\sigma$	$r$	$t$	$\alpha = (x, y)$	$\beta$	$\mathfrak{A}_0$
3	0	1, 3	1, 5	$(1, 0)$	$(\frac{t-1}{2}, 1)$	$\langle (-1, 0) \rangle$
3	0	1	3, 7	$(1, 0)$	$(-1, 0)$	$\langle (-1, 0) \rangle$
4	0	1, 3	5	$x = 2, y \equiv 3 \pmod{4},  \alpha  = 2^{\lambda-2}$	$(-1, 0)$	$\langle -\alpha^2 \rangle$
$\geq 4$	0	1, 3	1	$x \equiv 1 \pmod{4}, y = 4,  \alpha  = 2^{\lambda-3}$	$(0, 1)$	$\langle \alpha \rangle$
$\geq 4$	0	1	3, 7	$x \equiv 1 \pmod{4}, y = 4,  \alpha  = 2^{\lambda-3}$	$(-1, 0)$	$\langle \alpha \rangle$
$\geq 5$	0	1, 3	5	$x = 2, y \equiv 3 \pmod{4},  \alpha  = 2^{\lambda-2}$	$(-1, 0)$	$\langle \alpha \rangle$
$\geq 3$	1, 2	1, 3, 5, 7	1, 3, 5, 7	$x \equiv 1 \pmod{4}, y = 2,  \alpha  = 2^{\lambda-\sigma-2}$	$(-1, 0)$	$\langle \alpha \rangle$
$\geq 3$	$\geq 3$	1, 3, 5, 7	1, 3, 5, 7	$x \equiv 1 \pmod{4}, y = 1,  \alpha  = 2^{\lambda-\sigma-1}$	$(-1, 0)$	$\langle \alpha \rangle$

#### 2.2.4 Type R, unary and extremal cases

This section covers the unary and extremal cases of type  $R$ .

First, in the unary family, we have  $p$  odd and  $\sigma = \lambda$ . Then the second factor of  $M$  is trivial (and hence  $t$  is irrelevant). We then denote  $R_{p^\lambda}(r) = R(p, \lambda, \lambda, r, t)$ . In this case, we do not decompose  $W(M, Q)$  using characters: instead, if  $\lambda \leq 2$ , then  $W(M, Q)$  contains two distinct irreducible subrepresentations of level  $p^\lambda$ , denoted  $R_{p^\lambda}(r)_\pm$ ; otherwise, it contains a single such subrepresentation, denoted  $R_{p^\lambda}(r)_1$ . The unary family is handled by `SL2IrrepRUnary` (3.3.3) (which is called by `SL2IrrepR` (3.3.2) when appropriate).

Second, in the extremal family, we have  $p = 2$ ,  $\lambda \geq 2$ , and  $\sigma = \lambda - 2$ . Then the second factor of  $M$  is isomorphic to  $\mathbb{Z}/2\mathbb{Z}$ , and collapses in  $2M$ . Here,  $\text{Aut}(M, Q)$  is itself abelian, so we let  $\mathfrak{A} = \text{Aut}(M, Q)$ . This group has order 1, 2, or 4, with the following structure:

- For  $\lambda = 2$  and  $t = 1$ ,  $\mathfrak{A} = \langle \tau \rangle$  where  $\tau : (x, y) \mapsto (y, x)$ , and  $\mathfrak{A}_0 = \mathfrak{A} = \langle \tau \rangle$ .
- For  $\lambda = 2$  and  $t = 3$ ,  $\mathfrak{A}$  is trivial; there are no primitive characters.
- For  $\lambda = 3$  or  $4$ ,  $\mathfrak{A} = \{\pm 1\}$  acting on  $M$  by multiplication; there are no primitive characters.
- Finally, for  $\lambda \geq 5$ ,  $\mathfrak{A} = \text{Aut}(M, Q) = \langle \alpha \rangle \times \langle -1 \rangle$  with  $\alpha$  of order 2, and  $\mathfrak{A}_0 = \langle \alpha \rangle$ . Note that, for this special case, the usual test for primitivity (described in Section 2.1) fails, as there are no elements of  $\mathfrak{A}$  fixing  $2M$  pointwise.

The extremal family is handled by `SL2ModuleR` (3.3.1) and `SL2IrrepR` (3.3.2), just like the generic case.

## Chapter 3

# Irreducible representations of prime-power level

Methods for generating individual irreducible representations of  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$  for a given level  $p^\lambda$ .

After generating a representation  $\rho$  by means of the bases in [NW76], we perform a change of basis that results in a symmetric representation equivalent to  $\rho$ .

In each case (except the unary type  $R$ , for which see `SL2IrrepRUnary` (3.3.3)), the underlying module  $M$  is of rank 2, so its elements have the form  $(x, y)$  and are thus represented by lists  $[x, y]$ .

Characters of the abelian group  $\mathfrak{A} = \langle \alpha \rangle \times \langle \beta \rangle$  have the form  $\chi_{i,j}$ , given by

$$\chi_{i,j}(\alpha^v \beta^w) \mapsto \mathbf{e}\left(\frac{vi}{|\alpha|}\right) \mathbf{e}\left(\frac{wj}{|\beta|}\right),$$

where  $i$  and  $j$  are integers. We therefore represent each character by a list  $[i, j]$ . Note that in some cases  $\alpha$  or  $\beta$  is trivial, and the corresponding index  $i$  or  $j$  is therefore irrelevant.

We write  $p=p$ ,  $\text{lambda}=\lambda$ ,  $\text{sigma}=\sigma$ , and  $\text{chi}=\chi$ .

### 3.1 Representations of type D

See Section 2.2.1.

#### 3.1.1 SL2ModuleD

▷ `SL2ModuleD(p, lambda)` (function)

**Returns:** a record `rec(Agrp, Bp, Char, IsPrim)` describing  $(M, Q)$ .

Constructs information about the underlying quadratic module  $(M, Q)$  of type  $D$ , for  $p$  a prime and  $\lambda \geq 1$ .

`Agrp` is a list describing the elements of  $\mathfrak{A}$ . Each element  $a \in \mathfrak{A}$  is represented in `Agrp` by a list  $[v, a, a\_inv]$ , where  $v$  is a list defined by  $a = \alpha^{v[1]} \beta^{v[2]}$ . Note that  $\beta$  is trivial, and hence  $v[2]$  is irrelevant, when  $\mathfrak{A}$  is cyclic.

`Bp` is a list of representatives for the  $\mathfrak{A}$ -orbits on  $M^\times$ , which correspond to a basis for the  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ -invariant subspace associated to any primitive character  $\chi \in \widehat{\mathfrak{A}}$  with  $\chi^2 \neq 1$ . This is the basis given by [NW76], which may result in a non-symmetric representation; if this occurs, we perform a change of basis in `SL2IrrepD` (3.1.2) to obtain a symmetric representation. For non-primitive characters, we must use different bases which are particular to each case.

`Char(i, j)` converts two integers  $i, j$  to a function representing the character  $\chi_{i,j} \in \widehat{\mathfrak{A}}$ .  
`IsPrim(chi)` tests whether the output of `Char(i, j)` represents a primitive character.

### 3.1.2 SL2IrrepD

▷ `SL2IrrepD(p, lambda, chi_index)` (function)

**Returns:** a list of lists of the form  $[S, T]$ .

Constructs the modular data for the irreducible representation(s) of type  $D$  with level  $p^\lambda$ , for  $p$  a prime and  $\lambda \geq 1$ , corresponding to the character  $\chi$  indexed by `chi_index = [i, j]` (see the discussion of `Char(i, j)` in `SL2ModuleD` (3.1.1)).

Here  $S$  is symmetric and unitary and  $T$  is diagonal.

Depending on the parameters,  $W(M, Q)$  will contain either 1 or 2 such irreps.

## 3.2 Representations of type N

See Section 2.2.2.

### 3.2.1 SL2ModuleN

▷ `SL2ModuleN(p, lambda)` (function)

**Returns:** a record `rec(Agrp, Bp, Char, IsPrim, Nm, Prod)` describing  $(M, Q)$ .

Constructs information about the underlying quadratic module  $(M, Q)$  of type  $N$ , for  $p$  a prime and  $\lambda \geq 1$ .

`Agrp` is a list describing the elements of  $\mathfrak{A}$ . Each element  $a \in \mathfrak{A}$  is represented in `Agrp` by a list  $[v, a]$ , where  $v$  is a list defined by  $a = \alpha^{v[1]} \beta^{v[2]}$ . Note that  $\alpha$  is trivial, and hence  $v[1]$  is irrelevant, when  $\mathfrak{A}$  is cyclic.

`Bp` is a list of representatives for the  $\mathfrak{A}$ -orbits on  $M^\times$ , which correspond to a basis for the  $SL_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ -invariant subspace associated to any primitive character  $\chi \in \widehat{\mathfrak{A}}$  with  $\chi^2 \neq 1$ . This is the basis given by [NW76], which may result in a non-symmetric representation; if this occurs, we perform a change of basis in `SL2IrrepD` (3.1.2) to obtain a symmetric representation. For non-primitive characters, we must use different bases which are particular to each case.

`Char(i, j)` converts two integers  $i, j$  to a function representing the character  $\chi_{i,j} \in \widehat{\mathfrak{A}}$ .

`IsPrim(chi)` tests whether the output of `Char(i, j)` represents a primitive character.

`Nm(a)` and `Prod(a, b)` are the norm and product functions on  $M$ , respectively.

### 3.2.2 SL2IrrepN

▷ `SL2IrrepN(p, lambda, chi_index)` (function)

**Returns:** a list of lists of the form  $[S, T]$ .

Constructs the modular data for the irreducible representation(s) of type  $N$  with level  $p^\lambda$ , for  $p$  a prime and  $\lambda \geq 1$ , corresponding to the character  $\chi$  indexed by `chi_index = [i, j]` (see the discussion of `Char(i, j)` in `SL2ModuleN` (3.2.1)).

Here  $S$  is symmetric and unitary and  $T$  is diagonal.

Depending on the parameters,  $W(M, Q)$  will contain either 1 or 2 such irreps.

### 3.3 Representations of type R

See Section 2.2.3.

#### 3.3.1 SL2ModuleR

▷ SL2ModuleR(*p*, *lambda*, *sigma*, *r*, *t*) (function)

**Returns:** a record `rec(Agrp, Bp, Char, IsPrim, Nm, Ord, Prod, c, tM)` describing  $(M, Q)$ .

Constructs information about the underlying quadratic module  $(M, Q)$  of type  $R$ , for  $p$  a prime. The additional parameters  $\lambda$ ,  $\sigma$ ,  $r$ , and  $t$  should be integers chosen as follows.

If  $p$  is an odd prime, let  $\lambda \geq 2$ ,  $\sigma \in \{1, \dots, \lambda - 1\}$ , and  $r, t \in \{1, u\}$  with  $u$  a quadratic non-residue mod  $p$ . Note that  $\sigma = \lambda$  is a valid choice for type  $R$ , however, this gives the unary case, and so is not handled by this function, as it is decomposed in a different way; for this case, use SL2IrrepUnary (3.3.3) instead.

If  $p = 2$ , let  $\lambda \geq 2$ ,  $\sigma \in \{0, \dots, \lambda - 2\}$  and  $r, t \in \{1, 3, 5, 7\}$ .

`Agrp` is a list describing the elements of  $\mathfrak{A}$ . Each element  $a$  of  $\mathfrak{A}$  is represented in `Agrp` by a list  $[v, a]$ , where  $v$  is a list defined by  $a = \alpha^{v[1]} \beta^{v[2]}$ .

`Bp` is a list of representatives for the  $\mathfrak{A}$ -orbits on  $M^\times$ , which correspond to a basis for the  $SL_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ -invariant subspace associated to any primitive character  $\chi \in \widehat{\mathfrak{A}}$  with  $\chi^2 \neq 1$ . This is the basis given by [NW76], which may result in a non-symmetric representation; if this occurs, we perform a change of basis in SL2IrrepD (3.1.2) to obtain a symmetric representation. For non-primitive characters, we must use different bases which are particular to each case.

`Char(i, j)` converts two integers  $i, j$  to a function representing the character  $\chi_{i,j} \in \widehat{\mathfrak{A}}$ .

`IsPrim(chi)` tests whether the output of `Char(i, j)` represents a primitive character.

`Nm(a)`, `Ord(a)`, and `Prod(a, b)` are the norm, order, and product functions on  $M$ , respectively.

`c` is a scalar used in calculating the  $S$ -matrix; namely  $c = \frac{1}{|M|} \sum_{x \in M} \mathbf{e}(Q(x))$ . Note that this is equal to  $S_Q(-1)/\sqrt{|M|}$ , where  $S_Q(-1)$  is the central charge (see Section 2.1.1).

`tM` is a list describing the elements of the group  $M - pM$ .

#### 3.3.2 SL2IrrepR

▷ SL2IrrepR(*p*, *lambda*, *sigma*, *r*, *t*, *chi\_index*) (function)

**Returns:** a list of lists of the form  $[S, T]$ .

Constructs the modular data for the irreducible representation(s) of type  $R$  with parameters  $p$ ,  $\lambda$ ,  $\sigma$ ,  $r$ , and  $t$ , corresponding to the character  $\chi$  indexed by `chi_index = [i, j]` (see the discussions of  $\sigma$ ,  $r$ ,  $t$ , and `Char(i, j)` in SL2ModuleR (3.3.1)).

Here  $S$  is symmetric and unitary and  $T$  is diagonal.

Depending on the parameters,  $W(M, Q)$  will contain either 1 or 2 such irreps.

If  $\sigma = \lambda$  for  $p \neq 2$ , then the second factor of  $M$  is trivial (and hence  $t$  is irrelevant), so this falls through to SL2IrrepUnary (3.3.3).

#### 3.3.3 SL2IrrepUnary

▷ SL2IrrepUnary(*p*, *lambda*, *r*) (function)

**Returns:** a list of lists of the form  $[S, T]$ .

Constructs the modular data for the irreducible representation(s) of unary type  $R$  (that is, the special case where  $\sigma = \lambda$ ) with  $p$  an odd prime,  $\lambda$  a positive integer, and  $r \in \{1, u\}$  with  $u$  a quadratic non-residue mod  $p$ .

Here  $S$  is symmetric and unitary and  $T$  is diagonal.

In this case,  $W(M, Q)$  always contains exactly 2 such irreps.

## Chapter 4

# Lists of representations

The *degree* of a representation is also known as the *dimension*. The *level* of the congruent representation determined by the pair  $(S, T)$  is equal to the order of  $T$ .

We assign to each representation a *name* according to the conventions of [NW76].

### 4.1 Lists by degree

#### 4.1.1 SL2IrrepsOfDegree

- ▷ `SL2IrrepsOfDegree(degree)` (function)  
**Returns:** a list of records of the form `rec(S, T, degree, level, name)`.  
Constructs a list of all irreps of  $SL_2(\mathbb{Z})$  that have the given degree.

#### 4.1.2 SL2IrrepsOfMaxDegree

- ▷ `SL2IrrepsOfMaxDegree(maximum_degree)` (function)  
**Returns:** a list of records of the form `rec(S, T, degree, level, name)`.  
Constructs a list of all irreps of  $SL_2(\mathbb{Z})$  that have at most the given maximum degree.

### 4.2 Lists by level

#### 4.2.1 SL2IrrepsOfLevel

- ▷ `SL2IrrepsOfLevel(level)` (function)  
**Returns:** a list of records of the form `rec(S, T, degree, level, name)`.  
Constructs a list of all irreps of  $SL_2(\mathbb{Z})$  with the given level.

### 4.3 Lists of exceptional representations

#### 4.3.1 SL2IrrepsExceptional

- ▷ `SL2IrrepsExceptional(arg)` (function)  
**Returns:** a list of records of the form `rec(S, T, degree, level, name)`.  
Constructs a list of the 18 exceptional irreps of  $SL_2(\mathbb{Z})$ .

## Chapter 5

# Methods for testing

By the Chinese Remainder Theorem, it suffices to test irreps of prime power level, so those are the irreps handled by the functions in this section.

### 5.1 Testing

#### 5.1.1 SL2WithConjClasses

▷ `SL2WithConjClasses(p, lambda)` (function)

**Returns:** the group  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$  with conjugacy classes set to the format we use.

#### 5.1.2 SL2ChiST

▷ `SL2ChiST(S, T, p, lambda)` (function)

**Returns:** a list representing a character of  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ .

Converts the modular data  $(S, T)$ , which must have level dividing  $p^\lambda$ , into a character of  $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$ , presented in a form matching the conjugacy classes used in `SL2WithConjClasses`.

#### 5.1.3 SL2TestPositions

▷ `SL2TestPositions(p, lambda)` (function)

**Returns:** a boolean.

Constructs and tests all non-trivial irreps of level dividing  $p^\lambda$  by checking their positions in  $\mathrm{Irr}(G)$  (see [Section 71.8-2 of the GAP Manual](#)). Note that this function will print information on the irreps involved if `InfoSL2Reps` is set to level 1 or higher; see [Section 1.2](#).

#### 5.1.4 SL2TestSymmetry

▷ `SL2TestSymmetry(p, lambda)` (function)

**Returns:** a boolean.

Constructs and tests all irreps of level  $p^\lambda$ , confirming that the  $S$ -matrix is symmetric and unitary and the  $T$  matrix is diagonal. Note that this function will print information on the irreps involved if `InfoSL2Reps` is set to level 1 or higher; see [Section 1.2](#).



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