SL2Reps

Constructs representations of SL2(Z).

0.1

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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. The format is designed for the study of modular tensor categories in particular.

1.1 Installation

To install `SL2Reps`, first download it from `https://github.com/ontoclasm/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 `-l` 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 $\mathfrak{s}$ = `[[0,1],[-1,0]]` and $\mathfrak{t}$ = `[[1,1],[0,1]]` (which satisfy the relations $\mathfrak{s}^4 = (\mathfrak{s}\mathfrak{t})^3 = \mathrm{id}$). Thus, any complex representation ρ of $\mathrm{SL}_2(\mathbb{Z})$ on $\mathbb{C}^n$ (where $n \in \mathbb{Z}^+$ is called the *degree* of ρ) 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 ℓ is called the *level* of the representation. One may equivalently say that the kernel of the representation is a congruence subgroup. It has been shown that any representation of $\mathrm{SL}_2(\mathbb{Z})$ arising from a modular tensor category has this property [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. $\mathfrak{s}$ = `[[0,-1],[1,0]]` (under which convention the relations are $\mathfrak{s}^4 = \mathrm{id}$, $(\mathfrak{s}\mathfrak{t})^3 = \mathfrak{s}^2$). 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 ρ of $\mathrm{SL}_2(\mathbb{Z})$ can be decomposed into a direct sum of irreducible representations (irreps). Further, if ρ 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 λ.

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 $Q : M \to \mathbb{Q}/\mathbb{Z}$ 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 $M \times M \to \mathbb{Q}/\mathbb{Z}$.

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 $S_Q(-1)=\frac{1}{\sqrt{|M|}}\sum_{x\in M}\mathbf{e}(Q(x))$.

We may construct subrepresentations $W(M,Q,\chi)$ of $W(M,Q)$ 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 α and β. 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 $SL_2(\mathbb{Z}/p^\lambda\mathbb{Z})$-invariant subspace of V. We then denote by $W(M,Q,\chi)$ the subrepresentation of $W(M,Q)$ on V_χ. Note that $W(M,Q,\chi)\cong W(M,Q,\overline{\chi})$.

2.1.2 Primitive characters

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 ε 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 χ 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

The prime-power irreps then fall into three cases.

- The overwhelming majority are of the form $W(M,Q,\chi)$ for χ 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 χ 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.

All the finite-dimensional irreducible representations of $\mathrm{SL}_2(\mathbb{Z})$ 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

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

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^λ 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 $\mathrm{Aut}(M,Q)$; 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	λ	α	β	$\mathfrak{A}_0$
>2	1	1	$\lvert\beta\rvert = p-1$	$\langle 1\rangle$
>2	>1	$\lvert\alpha\rvert = p^{\lambda-1}$ (e.g. $\alpha = 1+p$)	$\lvert\beta\rvert = p-1$	$\langle\alpha\rangle$
2	2	1	-1	$\langle 1\rangle$
2	>2	$\lvert\alpha\rvert = 2^{\lambda-2}$ (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 $u \equiv 3 \bmod 4$ with $-u$ a quadratic non-residue mod p; if $p=2$, let $u=3$. Then the Weil representation arising from the quadratic module with

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

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^λ may be constructed via `SL2IrrepN` (3.2.2).

The additive group M is a ring with multiplication given by

$$(x_1,y_1)\cdot(x_2,y_2) = (x_1x_2 - \frac{1+u}{4}y_1y_2, x_1y_2 + x_2y_1 + y_1y_2)$$

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

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

of $M^\times$ acts on M by multiplication and is identified with a subgroup of $\mathrm{Aut}(M,Q)$; 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	λ	α	β	$\mathfrak{A}_0$
>2	1	$(1,0)$	$\lvert\beta\rvert = p+1$	$\langle(1,0)\rangle$
>2	>1	$\lvert\alpha\rvert = p^{\lambda-1}$	$\lvert\beta\rvert = p+1$	$\langle\alpha\rangle$
2	1	$(1,0)$	$\lvert\beta\rvert = 3$	$\langle(1,0)\rangle$
2	2	$(1,0)$	$\lvert\beta\rvert = 6$	$\langle(-1,0)\rangle$
2	>2	$\lvert\alpha\rvert = p^{\lambda-2}$	$\lvert\beta\rvert = 6$	$\langle\alpha\rangle$

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: σ, r, and t. Details are as follows:

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

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

  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 $\lambda \geq 2$, $\sigma \in \{0,\ldots,\lambda-2\}$ and $r,t \in \{1,3,5,7\}$. Then define

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

  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

$$(x_1,y_1)\cdot(x_2,y_2) = (x_1x_2 - p^{\sigma}ty_1y_2, x_1y_2 + x_2y_1)$$

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

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

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

The multiplicative subgroup

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

of $M^{\times}$ acts on M by multiplication and is identified with a subgroup of $\mathrm{Aut}(M,Q)$; 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, λ, σ, 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	λ	σ	(r,t)	α	β	$\mathfrak{A}_0$
3	2	1	$r,t \in \{1,2\}$	$\|\alpha\| = 3$	$(-1,0)$	$\langle\alpha\rangle$
3	≥ 3	1	$t = 1, r \in \{1,2\}$	$\|\alpha\| = 3^{\lambda-\sigma-1}$	$\|\beta\| = 6$	$\langle\alpha\rangle$
3	≥ 3	1	$t = 2, r \in \{1,2\}$	$\|\alpha\| = 3^{\lambda-\sigma}$	$(-1,0)$	$\langle\alpha\rangle$
3	≥ 3	$2,\dots,\lambda-1$	$r,t \in \{1,2\}$	$\|\alpha\| = 3^{\lambda-\sigma}$	$(-1,0)$	$\langle\alpha\rangle$
≥ 5	≥ 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, λ, σ, 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.

λ	σ	r	t	$\alpha = (x,y)$	β	$\mathfrak{A}_0$
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	$x = 2, y \equiv 3 \bmod 4, \|\alpha\| = 2^{\lambda-2}$	$(-1,0)$	$\langle-\alpha^2\rangle$
≥ 4	0	1,3	1	$x \equiv 1 \bmod 4, y = 4, \|\alpha\| = 2^{\lambda-3}$	$(0,1)$	$\langle\alpha\rangle$
≥ 4	0	1	3,7	$x \equiv 1 \bmod 4, y = 4, \|\alpha\| = 2^{\lambda-3}$	$(-1,0)$	$\langle\alpha\rangle$
≥ 5	0	1,3	5	$x = 2, y \equiv 3 \bmod 4, \|\alpha\| = 2^{\lambda-2}$	$(-1,0)$	$\langle\alpha\rangle$
≥ 3	1,2	1,3,5,7	1,3,5,7	$x \equiv 1 \bmod 4, y = 2, \|\alpha\| = 2^{\lambda-\sigma-2}$	$(-1,0)$	$\langle\alpha\rangle$
≥ 3	≥ 3	1,3,5,7	1,3,5,7	$x \equiv 1 \bmod 4, y = 1, \|\alpha\| = 2^{\lambda-\sigma-1}$	$(-1,0)$	$\langle\alpha\rangle$

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^λ, 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, $\mathrm{Aut}(M,Q)$ is itself abelian, so we let $\mathfrak{A} = \mathrm{Aut}(M,Q)$. 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 $\lambda \geq 5$, $\mathfrak{A} = \mathrm{Aut}(M,Q) = \langle\alpha\rangle \times \langle-1\rangle$ with α 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^λ.

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 α or β is trivial, and the corresponding index i or j is therefore irrelevant.

We write `p`=p, `lambda`=λ, `sigma`=σ, and `chi`=χ.

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 $a = \alpha^{\mathrm{v}[1]}\beta^{\mathrm{v}[2]}$. Note that β 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 $\chi^2 \not\equiv 1$. For other 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^λ, for p a prime and $\lambda \geq 1$, corresponding to the character χ indexed by `chi_index = [i,j]` (see the discussion of `Char(i,j)` in `SL2ModuleD` (3.1.1)).

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 $a = \alpha^{\mathtt{v[1]}}\beta^{\mathtt{v[2]}}$. Note that α 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 $\mathrm{SL}_2(\mathbb{Z}/p^\lambda\mathbb{Z})$-invariant subspace associated to any primitive character $\chi \in \widehat{\mathfrak{A}}$ with $\chi^2 \not\equiv 1$. For other 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^λ, for p a prime and $\lambda \geq 1$, corresponding to the character χ indexed by `chi_index = [i,j]` (see the discussion of `Char(i,j)` in `SL2ModuleN` (3.2.1)).

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 λ, σ, 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 `SL2IrrepRUnary` (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 $a = \alpha^{\mathtt{v[1]}}\beta^{\mathtt{v[2]}}$.

`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 $\chi^2 \not\equiv 1$. For other 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, λ, σ, r, and t, corresponding to the character χ indexed by `chi_index = [i,j]` (see the discussions of σ, r, t, and `Char(i,j)` in `SL2ModuleN` (3.2.1)).

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 `SL2IrrepRUnary` (3.3.3).

3.3.3 SL2IrrepRUnary

▷ `SL2IrrepRUnary(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, λ a positive integer, and $r \in \{1,u\}$ with u a quadratic non-residue mod p.

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 SL2PrimePowerIrrepsOfDegree

▷ `SL2PrimePowerIrrepsOfDegree(`*degree*`)` (function)

Returns: a list of records of the form `rec(S, T, degree, level, name)`.

Constructs a list of all irreps of $\mathrm{SL}_2(\mathbb{Z})$ that have the given degree and prime power level.

4.1.2 SL2PrimePowerIrrepsOfDegreeAtMost

▷ `SL2PrimePowerIrrepsOfDegreeAtMost(`*max_degree*`)` (function)

Returns: a list of records of the form `rec(S, T, degree, level, name)`.

Constructs a list of all irreps of $\mathrm{SL}_2(\mathbb{Z})$ that have degree at most `max_degree` and prime power level.

4.1.3 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 $\mathrm{SL}_2(\mathbb{Z})$ that have the given degree.

4.1.4 SL2IrrepsOfDegreeAtMost

▷ `SL2IrrepsOfDegreeAtMost(`*max_degree*`)` (function)

Returns: a list of records of the form `rec(S, T, degree, level, name)`.

Constructs a list of all irreps of $\mathrm{SL}_2(\mathbb{Z})$ that have degree at most `max_degree`.

4.2 Lists by level

4.2.1 SL2PrimePowerIrrepsOfLevel

▷ `SL2PrimePowerIrrepsOfLevel(p, lambda)` (function)

Returns: a list of records of the form `rec(S, T, degree, level, name)`.

Constructs a list of all irreps of $\mathrm{SL}_2(\mathbb{Z})$ with level exactly p^λ.

4.3 Lists of exceptional representations

4.3.1 SL2ExceptionalIrreps

▷ `SL2ExceptionalIrreps(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 $\mathrm{SL}_2(\mathbb{Z})$.

Chapter 5

Methods for testing

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^λ, 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 SL2IrrepPositionTest

▷ `SL2IrrepPositionTest(p, lambda)` (function)

Returns: a boolean.

Constructs and tests all irreps of level dividing p^λ by checking their positions in `Irr(G)`.

References

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