

A geometric realisation of affine 0-Schur algebras.

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Chapter 1

Introduction

Chapter 2

**Background: The double flag variety
approach to q -Schur algebras**

Chapter 3

The cyclic flags approach to affine q -Schur algebras

Fix natural numbers n and r .

Definition 3.0.1 (compositions). *A composition of r into n parts is an n -tuple $\lambda = (\lambda_1, \dots, \lambda_n) \in \mathbb{Z}^n$ of non-negative integers whose sum equals r . Denote the set of compositions of r into n parts by Λ_0 .*

Definition 3.0.2 (infinite periodic matrices). *Let Λ_1 be the set of matrices $A = (a_{i,j})_{i,j \in \mathbb{Z}}$ with integer entries $a_{i,j}$ satisfying the following conditions:*

- $a_{i,j} \geq 0$ for each $i, j \in \mathbb{Z}$;
- each row or column has only finitely many non-zero entries;
- the sum of the entries in any n consecutive rows or columns equals r ;
- $a_{i-n,j-n} = a_{i,j}$ for each $i, j \in \mathbb{Z}$.

These matrices are referred to as infinite periodic matrices.

Definition 3.0.3 (source and target). *Given $A \in \Lambda_1$, let $\text{ro}(A)$ and $\text{co}(A)$ be the compositions of r into n parts given by*

$$\text{ro}(A) = \left(\sum_{j \in \mathbb{Z}} a_{1,j}, \dots, \sum_{j \in \mathbb{Z}} a_{n,j} \right)$$

and

$$\text{co}(A) = \left(\sum_{i \in \mathbb{Z}} a_{i,1}, \dots, \sum_{i \in \mathbb{Z}} a_{i,n} \right).$$

$A \in \Lambda_1$ is said to go from $\text{co}(A)$ to $\text{ro}(A)$.

Definition 3.0.4 (diagonal matrices). *Given $\lambda \in \Lambda_0$, let $D_\lambda \in \Lambda_1$ be the matrix given by $(D_\lambda)_{i,j} = 0$ for $i, j \in \mathbb{Z}$ with $i \neq j$ and $(D_\lambda)_{i,i} = \lambda_i$ for $i \in \mathbb{Z}$; where the indices are taken modulo n .*

3.1 Cyclic flags

Fix $n, r \in \mathbb{N}$ and let \mathbf{k} be a field. Let \mathcal{S} be the \mathbf{k} -algebra $\mathbf{k}[\varepsilon, \varepsilon^{-1}]$ and let \mathcal{R} be the subalgebra generated by ε , so $\mathcal{R} = \mathbf{k}[\varepsilon]$. Let V be a free \mathcal{S} -module of rank r . Let G be the automorphism group of the \mathcal{S} -module V , so G is isomorphic to $\mathrm{GL}_r(\mathcal{S})$. A lattice in V is a \mathcal{R} -submodule L of V with $\mathcal{S} \otimes_{\mathcal{R}} L = V$. In particular, a lattice is an \mathcal{R} -submodule of V which is a free \mathcal{R} -module of rank r .

Lemma 3.1.1. *Let L be a lattice in V . $L/\varepsilon L$ is a torsion \mathcal{R} -module, where ε acts as zero. $L/\varepsilon L$ is a free $\mathcal{R}/\langle \varepsilon \rangle$ -module of rank r ; that is, $L/\varepsilon L$ is an r -dimensional \mathbf{k} -vector space.*

Proof. L is a free \mathcal{R} -module of rank r , with $L \subset V$. Given an \mathcal{R} -basis $\{x_1, \dots, x_r\}$ of L , $\{\varepsilon x_1, \dots, \varepsilon x_r\}$ is an \mathcal{R} -basis of εL . Finally, the cosets $\{x_1 + \varepsilon L, \dots, x_r + \varepsilon L\}$ give a basis for $L/\varepsilon L$ over $\mathcal{R}/\langle \varepsilon \rangle \cong \mathbf{k}$. \square

Let $\mathcal{F} = \mathcal{F}_{\mathbf{k}}(n, r)$ be the set of collections $(L_i)_{i \in \mathbb{Z}}$ of lattices in V with $L_i \subset L_{i+1}$ and $\varepsilon L_i = L_{i-n}$ for each $i \in \mathbb{Z}$. These collections of lattices in V are referred to as cyclic flags in V .

G acts on \mathcal{F} by $(g \cdot L)_i = g(L_i)$ for each $i \in \mathbb{Z}$, $g \in G$ and $L \in \mathcal{F}$. The G -orbits in \mathcal{F} are indexed by the set Λ_0 of compositions of r into n parts. In particular, the G -orbit in \mathcal{F} corresponding to $\lambda \in \Lambda_0$ is

$$\mathcal{F}_\lambda = \left\{ L \in \mathcal{F} : \dim \left(\frac{L_i}{L_{i-1}} \right) = \lambda_i \text{ for each } i \in \mathbb{Z} \right\}$$

Definition 3.1.1. *The periodic characteristic matrix of a pair of cyclic flags $(L, L') \in \mathcal{F} \times \mathcal{F}$ is the matrix $A(L, L') = (a_{i,j})_{i,j \in \mathbb{Z}}$ with entries*

$$a_{i,j} = \dim_{\mathbf{k}} \left(\frac{L_i \cap L'_j}{L_i \cap L'_{j-1} + L_{i-1} \cap L'_j} \right)$$

for each $i, j \in \mathbb{Z}$.

The diagonal action of G on $\mathcal{F} \times \mathcal{F}$ has orbits indexed by the set Λ_1 of infinite periodic matrices (see definition 3.0.2). The G -orbit corresponding to $A \in \Lambda_1$ is denoted \mathcal{O}_A and consists of those pairs $(L, L') \in \mathcal{F} \times \mathcal{F}$ with periodic characteristic matrix $A(L, L')$ equal to A .

Lemma 3.1.2. *(alternative expression for characteristic matrix) Alternatively,*

$$a_{i,j} = \dim_{\mathbf{k}} \left(\frac{L_{i-1} + L_i \cap L'_j}{L_{i-1} + L_i \cap L'_{j-1}} \right)$$

for each $i, j \in \mathbb{Z}$.

Proof. Set $U = L_i \cap L'_j$ and $U' = L_{i-1} + L_i \cap L'_{j-1}$. Then $U + U' = L_{i-1} + L_i \cap L'_j$ and $U \cap U' = L_i \cap L'_j \cap L_{i-1} + L_i \cap L'_{j-1}$. Applying the isomorphism theorems, $U + U'/U'$ is naturally isomorphic to $U/U \cap U'$ as a vector space. In particular,

$$\frac{L_{i-1} + L_i \cap L'_j}{L_{i-1} + L_i \cap L'_{j-1}} = \frac{L_i \cap L'_j}{L_{i-1} \cap L'_j + L_i \cap L'_{j-1}}$$

and thus the dimensions of these spaces are both equal to $a_{i,j}$. \square

Lemma 3.1.3 (transposing characteristic matrix). *Given a pair of flags $(L, L') \in \mathcal{F}^2$, the matrices $A(L, L')$ and $A(L', L)$ are related by the transpose. In particular, $A(L, L')_{i,j} = A(L', L)_{j,i}$ for each $i, j \in \mathbb{Z}$.*

Proof. By swapping the roles of i and j and swapping L and L' it is clear that $A(L, L')_{i,j}$ and $A(L', L)_{j,i}$ are both given by the dimension of the \mathbf{k} -vector space

$$\frac{L_i \cap L'_j}{L_{i-1} \cap L'_j + L_i \cap L'_{j-1}},$$

for each $i, j \in \mathbb{Z}$. □

Lemma 3.1.4 (a codimension formula). *Given $(L, L') \in \mathcal{F}^2$ and $i, j \in \mathbb{Z}$,*

$$\dim_{\mathbf{k}} \left(\frac{L_i}{L_i \cap L'_j} \right) = \sum_{s \leq i, t > j} a_{s,t},$$

where $A(L, L') = (a_{i,j})_{i,j \in \mathbb{Z}}$.

Proof. **COMPLETE THIS PROOF** □

Lemma 3.1.5 (nested flags). *Given $(L, L') \in \mathcal{F}^2$, $L' \subset L$ if and only if $A(L, L')_{i,j} = 0$ for $i, j \in \mathbb{Z}$ with $i > j$.*

Proof. Suppose $L, L' \in \mathcal{F}$ with $L' \subset L$, meaning $L'_j \subset L_j$ for each $j \in \mathbb{Z}$. Then for $i > j$, $L_i \cap L'_j = L'_j$, $L_{i-1} \cap L'_j = L'_j$ and $L_i \cap L'_{j-1}$, which shows

$$A(L, L')_{i,j} = \dim_{\mathbf{k}} \left(\frac{L'_j}{L'_{j-1} + L'_j} \right) = 0$$

as required. Conversely, suppose $A(L, L')$ is upper triangular, meaning $A(L, L')_{i,j} = 0$ when $i > j$. Using Lemma 3.1.4,

$$\dim_{\mathbf{k}} \left(\frac{L'_i}{L'_i \cap L_i} \right) = \sum_{s > i, t \leq i} a_{s,t} = 0,$$

so $L_i \cap L'_i = L'_i$ and thus $L'_i \subset L_i$ for each $i \in \mathbb{Z}$, as required. □

Corollary 3.1.6 (diagonal orbits). *Given $L, L' \in \mathcal{F}$, $L = L'$ if and only if $A(L, L')_{i,j} = 0$ whenever $i \neq j$. In particular,*

$$\mathcal{O}_{D_\lambda} = \{(L, L) \in \mathcal{F}^2 : L \in \mathcal{F}_\lambda\},$$

for each $\lambda \in \Lambda_0$.

3.1.1 A product of orbits

Given $A, B \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$, define

$$Y_{A,B} = \{(L, L', L'') \in \mathcal{F}^3 : (L, L') \in \mathcal{O}_A \text{ and } (L', L'') \in \mathcal{O}_B\},$$

$$X_{A,B} = \{(L, L'') \in \mathcal{F}^2 : \exists L' \in \mathcal{F} \text{ with } (L, L') \in \mathcal{O}_A \text{ and } (L', L'') \in \mathcal{O}_B\}.$$

If also $L \in \mathcal{F}_{\text{ro}(A)}$, define the L -slices of $Y_{A,B}$ and $X_{A,B}$ respectively as

$$Y_{A,B}^L = \{(L', L'') \in \mathcal{F}^2 : (L, L', L'') \in Y_{A,B}\},$$

$$X_{A,B}^L = \{L'' \in \mathcal{F} : (L, L'') \in X_{A,B}\}.$$

Observation 1. *There are only finitely many G -orbits in $X_{A,B}$.*

Lemma 3.1.7. *Given $A \in \Lambda_1$, $X_{D_\lambda, A} = \mathcal{O}_A$ if $\lambda = \text{ro}(A)$ and $X_{A, D_\lambda} = \mathcal{O}_A$ if $\lambda = \text{co}(A)$.*

Proof. Let $A \in \Lambda_1$ and set $\lambda = \text{ro}(A)$. $Y_{D_\lambda, A}$ is the set of triples $(L, L', L'') \in \mathcal{F}^3$ with $(L, L') \in \mathcal{O}_{D_\lambda}$, thus $L = L'$ by Corollary 3.1.6, and $(L', L'') \in \mathcal{O}_A$. $X_{D_\lambda, A}$ is the projection of $Y_{D_\lambda, A}$, which equals \mathcal{O}_A .

Similarly, if $\lambda = \text{co}(A)$, Y_{A, D_λ} is the set of triples $(L, L', L'') \in \mathcal{F}^3$ with $(L, L') \in \mathcal{O}_A$ and $L'' = L'$, so X_{A, D_λ} is exactly the orbit \mathcal{O}_B . \square

3.1.2 Triple products

Given $A, B, C \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$ and $\text{co}(B) = \text{ro}(C)$ and $L \in \mathcal{F}_{\text{ro}(A)}$, there are spaces $X_{A,B,C}$, $Y_{A,B,C}$ and their respective L -slices, defined as follows:

$$Y_{A,B,C} = \{(L, L', L'', L''') \in \mathcal{F}^4 : (L, L') \in \mathcal{O}_A, (L', L'') \in \mathcal{O}_B \text{ and } (L'', L''') \in \mathcal{O}_C\},$$

$$X_{A,B,C} = \{(L, L''') \in \mathcal{F}^2 : \exists (L', L'') \in \mathcal{O}_B \text{ with } (L, L') \in \mathcal{O}_A \text{ and } (L'', L''') \in \mathcal{O}_C\},$$

$$Y_{A,B,C}^L = \{(L', L'', L''') \in \mathcal{F}^3 : (L, L', L'', L''') \in Y_{A,B,C}\},$$

$$X_{A,B,C}^L = \{L''' \in \mathcal{F} : (L, L''') \in X_{A,B,C}\}.$$

3.2 Convolution algebras

Suppose \mathbf{k} is a finite field and let q denote the number of elements of \mathbf{k} . Consider the set S of G -invariant functions $\mathcal{F} \times \mathcal{F} \rightarrow \mathbb{Z}$ with constructible support. S is a free \mathbb{Z} -module with a basis consisting of the indicator functions of the G -orbits in $\mathcal{F} \times \mathcal{F}$. Define an operation \star on S as follows: for each $f, g \in S$, $f \star g \in S$ is given by

$$(f \star g)(L, L'') = \sum_{L' \in \mathcal{F}} f(L, L')g(L', L''),$$

for $(L, L'') \in \mathcal{F} \times \mathcal{F}$.

$f \star g$ is well defined since the supports of f and g consist of finitely many G -orbits, so there are only finitely many $L' \in \mathcal{F}$ such that $f(L, L')g(L', L'') \neq 0$, given $(L, L'') \in \mathcal{F} \times \mathcal{F}$. $f \star g$ is constant on G -orbits and is supported on finitely many G -orbits, so $f \star g \in S$.

Lemma 3.2.1. *The set S together with the operation \star is an associative \mathbb{Z} -algebra with identity element ι given by $\iota(L, L) = 1$ and $\iota(L, L') = 0$ for $L' \neq L$.*

Proof. Given $f, g, h \in S$ and $(L, L''') \in \mathcal{F} \times \mathcal{F}$,

$$\begin{aligned} ((f \star g) \star h)(L, L''') &= \sum_{L''} (f \star g)(L, L'')h(L'', L''') \\ &= \sum_{L''} \sum_{L'} f(L, L')g(L', L'')h(L'', L''') \\ &= (f \star (g \star h))(L, L'''), \end{aligned}$$

thus \star is associative. ι is the multiplicative identity since

$$(\iota \star f)(L, L'') = \sum_{L'} \iota(L, L')f(L', L'') = f(L, L'')$$

and

$$(f \star \iota)(L, L'') = \sum_{L'} f(L, L') \iota(L', L'') = f(L, L''),$$

for each $f \in S$ and $(L, L'') \in \mathcal{F} \times \mathcal{F}$. □

Given $A \in \Lambda_1$, let $e_A \in S$ denote the indicator function of the orbit \mathcal{O}_A . S is a free \mathbb{Z} -module with basis $\{e_A : A \in \Lambda_1\}$. There exist $\gamma_{A,B,C;q} \in \mathbb{Z}$ for $A, B, C \in \Lambda_1$ such that

$$e_A \star e_B = \sum_{C \in \Lambda_1} \gamma_{A,B,C;q} e_C$$

for each $A, B \in \Lambda_1$. Then

$$\begin{aligned} \gamma_{A,B,C;q} &= (e_A \star e_B)(L, L'') \\ &= \sum_{L'} e_A(L, L') e_B(L', L'') \\ &= \#\{L' : (L, L') \in \mathcal{O}_A \text{ and } (L', L'') \in \mathcal{O}_B\}, \end{aligned}$$

for any $(L, L'') \in \mathcal{O}_C$.

3.3 Affine q-Schur algebras

There exist polynomials $\gamma_{A,B,C} \in \mathbb{Z}[q]$ for $A, B, C \in \Lambda_1$ such that $\gamma_{A,B,C}(q) = \gamma_{A,B,C;q}$ for any prime power q , following [32, section 4]. The affine q -Schur algebra $\hat{S}_q(n, r)$ is a $\mathbb{Z}[q]$ -algebra which is a free $\mathbb{Z}[q]$ -module with basis $\{e_A : A \in \Lambda_1\}$ and with multiplication given by

$$e_A e_B = \sum_C \gamma_{A,B,C} e_C.$$

Given the existence of these ‘universal polynomials’ $\gamma_{A,B,C} \in \mathbb{Z}[q]$, it follows from Lemma 3.2.1 that $\hat{S}_q(n, r)$ is an associative $\mathbb{Z}[q]$ -algebra with multiplicative identity given by

$$1 = \sum_{\lambda \in \Lambda_0} e_{D_\lambda}.$$

Chapter 4

Presenting affine q-Schur algebras

4.1 Basic results and notation

4.1.1 Elementary matrices

For each $i, j \in \mathbb{Z}$, let $\mathcal{E}_{i,j}$ be the $\mathbb{Z} \times \mathbb{Z}$ ‘elementary periodic matrix’ with entries given by $(\mathcal{E}_{i,j})_{s,t} = 1$ if $(s, t) = (i + cn, j + cn)$ for some $c \in \mathbb{Z}$ and $(\mathcal{E}_{i,j})_{s,t} = 0$ otherwise. Clearly $\mathcal{E}_{i,j} = \mathcal{E}_{i+n,j+n}$ for each $i, j \in \mathbb{Z}$. Recall from Definition 3.0.4 that the diagonal matrix associated to a composition $\lambda \in \Lambda_0$ is

$$D_\lambda = \lambda_1 \mathcal{E}_{1,1} + \cdots + \lambda_n \mathcal{E}_{n,n}.$$

$\{e_{D_\lambda} : \lambda \in \Lambda_0\}$ is a set of pairwise orthogonal idempotents in $\hat{S}_q(n, r)$ with $\sum_{\lambda \in \Lambda_0} e_{D_\lambda} = 1$, as a result of Lemma 3.1.7.

Given $i \in [1, n]$ and $\lambda \in \Lambda_0$ with $\lambda_{i+1} > 0$, define

$$E_{i,\lambda} = e_{D_\lambda + \mathcal{E}_{i,i+1} - \mathcal{E}_{i+1,i+1}}$$

and define

$$E_i = \sum_{\lambda \in \Lambda_0 : \lambda_{i+1} > 0} E_{i,\lambda}.$$

Given $i \in [1, n]$ and $\lambda \in \Lambda_0$ with $\lambda_i > 0$, define

$$F_{i,\lambda} = e_{D_\lambda + \mathcal{E}_{i+1,i} - \mathcal{E}_{i,i}}$$

and define

$$F_i = \sum_{\lambda \in \Lambda_0 : \lambda_i > 0} F_{i,\lambda}$$

4.1.2 Transpose involution

Lemma 4.1.1. *Transposition gives a homomorphism of $\mathbb{Z}[q]$ -modules $\top : \hat{S}_q(n, r) \rightarrow \hat{S}_q(n, r)$ with $\top(e_A) = e_{A^\top}$, $\top \circ \top = 1$ and $\top(e_A e_B) = \top(e_B) \top(e_A)$.*

Proof. Let $A, B, C \in \Lambda_1$ and let \mathbf{k} be a finite field with $q = \#\mathbf{k}$ elements. If $(L, L'') \in \mathcal{O}_C$ then $(L'', L) \in \mathcal{O}_{C^\top}$ and

$$\begin{aligned} \gamma_{A,B,C;q} &= \#\{L' : (L, L') \in \mathcal{O}_A \text{ and } (L', L'') \in \mathcal{O}_B\} \\ &= \#\{L' : (L'', L') \in \mathcal{O}_{B^\top} \text{ and } (L', L) \in \mathcal{O}_{A^\top}\} \\ &= \gamma_{B^\top, A^\top, C^\top;q} \end{aligned}$$

It then follows that $\top(e_A e_B) = \top(e_B) \top(e_A)$. \square

The transpose relates the E_i , F_i and 1_λ in the following way: $\top(E_{i,\lambda}) = F_{i,\lambda}$, $\top(F_{i,\lambda}) = E_{i,\lambda-\varepsilon_i+\varepsilon_{i+1}}$ and $\top(1_\lambda) = 1_\lambda$. In particular, $\top(E_i) = F_i$ and $\top(F_i) = E_i$.

4.1.3 A multiplication rule

Lemma 4.1.2. *Given $A \in \Lambda_1$ and $i \in [1, n]$ with $\text{ro}(A)_{i+1} > 0$,*

$$E_i e_A = \sum_{p \in \mathbb{Z}: a_{i+1,p} > 0} q^{\sum_{j>p} a_{i,j}} [[a_{i,p} + 1]] e_{A+\varepsilon_{i,p}-\varepsilon_{i+1,p}}.$$

Given $A \in \Lambda_1$ and $i \in [1, n]$ with $\text{ro}(A)_i > 0$,

$$F_i e_A = \sum_{p \in \mathbb{Z}: a_{i,p} > 0} q^{\sum_{j<p} a_{i+1,j}} [[a_{i+1,p} + 1]] e_{A+\varepsilon_{i+1,p}-\varepsilon_{i,p}}.$$

Note that these formulas are still valid in the cases $E_i e_A = 0$ and $F_i e_A = 0$, provided it is understood that $e_B = 0$ whenever $B \notin \Lambda_1$. There are similar formulas for right multiplication by E_i and F_i , obtained by applying the transpose involution to the above.

Corollary 4.1.3. *Given $A \in \Lambda_1$ and $j \in [1, n]$ with $\text{co}(A)_{j+1} > 0$,*

$$e_A F_j = \sum_{p \in \mathbb{Z}: a_{p,j+1} > 0} q^{\sum_{i>p} a_{i,j}} [[a_{p,j} + 1]] e_{A+\varepsilon_{p,j}-\varepsilon_{p,j+1}}.$$

Given $A \in \Lambda_1$ and $j \in [1, n]$ with $\text{co}(A)_j > 0$,

$$e_A E_j = \sum_{p \in \mathbb{Z}: a_{p,j} > 0} q^{\sum_{i<p} a_{i,j+1}} [[a_{p,j+1} + 1]] e_{A+\varepsilon_{p,j+1}-\varepsilon_{p,j}}.$$

Proof.

$$\begin{aligned} e_A F_j &= \top(E_j e_{A^\top}) \\ &= \top \left(\sum_{p \in \mathbb{Z}: a_{p,j+1} > 0} q^{\sum_{i>p} a_{i,j}} [[a_{p,j} + 1]] e_{A^\top+\varepsilon_{j,p}-\varepsilon_{j+1,p}} \right) \\ &= \sum_{p \in \mathbb{Z}: a_{p,j+1} > 0} q^{\sum_{i>p} a_{i,j}} [[a_{p,j} + 1]] e_{A+\varepsilon_{p,j}-\varepsilon_{p,j+1}}, \end{aligned}$$

where the second equality comes from Lemma 4.1.2. Similarly,

$$\begin{aligned} e_A E_j &= \top(F_j e_{A^\top}) \\ &= \top \left(\sum_{p \in \mathbb{Z}: a_{p,j} > 0} q^{\sum_{i<p} a_{i,j+1}} [[a_{p,j+1} + 1]] e_{A^\top+\varepsilon_{j+1,p}-\varepsilon_{j,p}} \right) \\ &= \sum_{p \in \mathbb{Z}: a_{p,j} > 0} q^{\sum_{i<p} a_{i,j+1}} [[a_{p,j+1} + 1]] e_{A+\varepsilon_{p,j+1}-\varepsilon_{p,j}}. \end{aligned}$$

\square

4.1.4 Shifting

Introduce the elements R_λ and R and prove that $SR = R^{-1}$. Also show multiplication by R acts as a shift along by one row or column according to whether R is acting on the left or the right.

For $\lambda \in \Lambda_0$, let $R_\lambda = e_{\lambda_1 \varepsilon_{0,1} + \dots + \lambda_n \varepsilon_{n-1,n}}$. Write $R = \sum_{\lambda \in \Lambda_0} R_\lambda$. Note $R_\lambda = R 1_\lambda$. Given $A \in \Lambda_1$ and $m \in \mathbb{Z}$, let $A[m] \in \Lambda_1$ be given by $A[m]_{i,j} = a_{i,j+m}$ and let $A^{[m]}$ be given by $A^{[m]}_{i,j} = a_{i+m,j}$ for each $i \in \mathbb{Z}$.

Lemma 4.1.4 (Shifting). *If $A \in \Lambda_1$ then*

$$Re_A = e_{A[\pm 1]}$$

and

$$e_A R = e_{A[\pm 1]}.$$

Conjugation by R gives an automorphism ρ of $\hat{S}_q(n, r)$ satisfying $\rho^n = 1$.

4.2 Relations

Note that $E_i^{r+1} = F_i^{r+1} = 0$ while

$$E_i^r = [r]! e_r \varepsilon_{i,i+1}$$

and

$$F_i^r = [r]! e_r \varepsilon_{i+1,i}.$$

Lemma 4.2.1 (quantum Serre relations: $n \geq 3$). *Suppose $n \geq 3$. The following relations hold in $\hat{S}_q(n, r)$:*

$$E_i E_j - E_j E_i = 0$$

$$F_i F_j - F_j F_i = 0$$

unless $j = i \pm 1$;

$$E_i E_{i+1}^2 - (1+q) E_{i+1} E_i E_{i+1} + q E_{i+1}^2 E_i = 0$$

$$E_i^2 E_{i+1} - (1+q) E_i E_{i+1} E_i + q E_{i+1} E_i^2 = 0$$

and

$$F_{i+1} F_i^2 - (1+q) F_i F_{i+1} F_i + q F_i^2 F_{i+1} = 0$$

$$F_{i+1}^2 F_i - (1+q) F_{i+1} F_i F_{i+1} + q F_i F_{i+1}^2 = 0.$$

Proof. Here we introduce temporary notation for the basis elements: Write $[A] = e_A$.

Take $\lambda \in \Lambda_0$.

$$E_i E_{i+1}^2 1_\lambda = [2][D_\lambda + 2X_{i+1,i+2} + X_{i,i+2}] + [2][D_\lambda + 2X_{i+1,i+2} + X_{i,i+1}]$$

$$E_{i+1} E_i E_{i+1} 1_\lambda = [D_\lambda + 2X_{i+1,i+2} + X_{i,i+1}] + [2][D_\lambda + 2X_{i+1,i+1} + X_{i,i+1}]$$

$$E_{i+1}^2 E_i 1_\lambda = [2][D_\lambda + 2X_{i+1,i+2} + X_{i,i+1}]$$

Then

$$(E_i E_{i+1}^2 - (1+q)E_{i+1}E_iE_{i+1} + qE_{i+1}^2E_i)1_\lambda = 0,$$

for each $\lambda \in \Lambda_0$. The relation $E_i E_{i+1}^2 - (1+q)E_{i+1}E_iE_{i+1} + qE_{i+1}^2E_i = 0$ then follows.

The relations between F_i and F_{i+1} may be obtained directly, as above, or by applying the transpose operator to the relations already derived: note that the two sets of relations are related by swapping E_i and F_i and reversing the order of multiplication. \square

Lemma 4.2.2 (quantum Serre relations: $n = 2$). *In the case $n = 2$, the quantum Serre relations will be of total degree 4. Look at the presentation of quantum groups for candidate relations. If that fails, brute force won't be too hard.*

Lemma 4.2.3. $[E_i, F_j] = 0$ unless $j = i$.

$$E_i F_i - F_i E_i = \sum_{\lambda \in \Lambda_0} ([\lambda_i] - [\lambda_{i+1}])1_\lambda.$$

Lemma 4.2.4. *The element R satisfies the following relations:*

$$RSR = 1 = SRR,$$

$$RE_i SR = E_{i-1},$$

$$RF_i SR = F_{i-1}.$$

Proof. **COMPLETE THIS.** \square

4.3 quivers with relations

Denote by Λ_0 the set of compositions of r into n parts. That is, Λ_0 is the set of $\alpha \in \mathbb{Z}^n$ with non-negative entries which sum to r . Let $\varepsilon_i \in \mathbb{Z}^n$ be the i th elementary vector and write $\alpha_i = \varepsilon_i - \varepsilon_{i+1}$ for each $i \in [1, n]$. Then $\lambda + \alpha_i \in \Lambda_0$ if $\lambda_{i+1} > 0$ and $\lambda - \alpha_i \in \Lambda_0$ if $\lambda_i > 0$.

Let $\Gamma = \Gamma(n, r)$ be the quiver with set of vertices Λ_0 , with the following arrows:

For $\lambda \in \Lambda_0$ and $i \in [1, n]$, there is an arrow $e_{i,\lambda} : \lambda \rightarrow \lambda + \alpha_i$ if $\lambda_{i+1} > 0$ and there is an arrow $f_{i,\lambda} : \lambda \rightarrow \lambda - \alpha_i$ if $\lambda_i > 0$.

Denote by $\mathbb{Z}[q]\Gamma$ the path $\mathbb{Z}[q]$ -algebra of Γ . Thus $\mathbb{Z}[q]\Gamma$ is a free $\mathbb{Z}[q]$ -module with a basis given by the set of paths in Γ , with multiplication given by the concatenation of paths. If p starts where q ends, the product pq is the path q followed by p . Write $e_{i,\lambda} = 0$ unless $\lambda, \lambda + \alpha_i \in \Lambda_0$ and write $f_{i,\lambda} = 0$ unless $\lambda, \lambda - \alpha_i \in \Lambda_0$.

By construction, there is a homomorphism of $\mathbb{Z}[q]$ -algebras

$$\phi : \mathbb{Z}[q]\Gamma \rightarrow \hat{S}_q(n, r)$$

given by

$$\phi(e_{i,\lambda}) = E_{i,\lambda}$$

$$\phi(f_{i,\lambda}) = F_{i,\lambda}$$

$$\phi(k_\lambda) = 1_\lambda,$$

for $i \in [1, n]$ and $\lambda \in \Lambda_0$.

The image of ϕ is the subalgebra of $\hat{S}_q(n, r)$ generated by E_i, F_i for $i \in [1, n]$ and 1_λ for $\lambda \in \Lambda_0$, since $E_{i,\lambda} = E_i 1_\lambda$ and $F_{i,\lambda} = F_i 1_\lambda$, while $E_i = \sum_\lambda E_{i,\lambda}$ and $F_i = \sum_\lambda F_{i,\lambda}$. In general ϕ is not surjective, so this does not always lead to a presentation of $\hat{S}_q(n, r)$.

4.3.1 Exceptional case $n=2$.

Describe the quiver.

Define an ideal of relations in the path algebra.

Write down the homomorphism from the bound quiver algebra to the q -Schur algebra.

4.3.2 Typical case.

Suppose $n \geq 3$. Then $\Gamma = \Gamma(n, r)$ has vertex set Λ_0 .

Define $e_i, f_i \in \mathbb{Z}[q]\Gamma(n, r)$ by

$$e_i = \sum_{\lambda \in \Lambda_0} e_{i,\lambda}$$

and

$$f_i = \sum_{\lambda \in \Lambda_0} f_{i,\lambda},$$

with the convention $e_{i,\lambda} = 0$ unless $\lambda_{i+1} > 0$ and $f_{i,\lambda} = 0$ unless $\lambda_i > 0$. Let k_λ denote the constant path at vertex λ . $\{k_\lambda : \lambda \in \Lambda_0\}$ is a set of pairwise orthogonal idempotents in $\mathbb{Z}[q]\Gamma(n, r)$.

Let $I(n, r) \subset \mathbb{Z}[q]\Gamma(n, r)$ be the ideal generated by the expressions

$$\begin{aligned} & e_i e_{i+1}^2 - (1+q)e_{i+1}e_i e_{i+1} + qe_{i+1}^2 e_i \\ & e_i^2 e_{i+1} - (1+q)e_i e_{i+1} e_i + qe_{i+1} e_i^2 \\ & f_{i+1} f_i^2 - (1+q)f_i f_{i+1} f_i + qf_i^2 f_{i+1} \\ & f_{i+1}^2 f_i - (1+q)f_{i+1} f_i f_{i+1} + qf_i f_{i+1}^2 \\ & e_i f_j - f_j e_i - \delta_{i,j} \sum_{\lambda \in \Lambda_0} ([\lambda_i] - [\lambda_{i+1}]) k_\lambda \end{aligned}$$

Recall that a relation is a $\mathbb{Z}[q]$ -linear combination of paths with common start and end vertices. The relations involving paths $\lambda \rightarrow \mu$ are given by $1_\mu \text{expr} 1_\lambda$, for each of the above expressions.

Lemma 4.3.1. *There is a homomorphism of $\mathbb{Z}[q]$ -algebras*

$$\phi: \mathbb{Z}[q]\Gamma(n, r)/I(n, r) \rightarrow \hat{S}_q(n, r)$$

given by

$$\begin{aligned} \phi(e_{i,\lambda}) &= E_{i,\lambda} \\ \phi(f_{i,\lambda}) &= F_{i,\lambda} \\ \phi(k_\lambda) &= 1_\lambda. \end{aligned}$$

Chapter 5

A generic affine algebra

5.1 Introduction

Assume $\mathbf{k} = \mathbb{C}$ and fix $n, r \geq 1$. Let \mathcal{S} be the \mathbf{k} -algebra $\mathbf{k}[\varepsilon, \varepsilon^{-1}]$ and let \mathcal{R} be the subalgebra generated by ε , namely $\mathcal{R} = \mathbf{k}[\varepsilon]$. Let V be a free \mathcal{S} -module of rank r and let $\mathcal{F} = \mathcal{F}_{\mathbf{k}}(n, r)$ be the set of n -periodic cyclic flags in V ; so \mathcal{F} consists of collections $L = (L_i)_{i \in \mathbb{Z}}$ of \mathcal{R} -lattices in V with $L_i \subset L_{i+1}$ for $i \in \mathbb{Z}$ and $\varepsilon L_i = L_{i-n}$ for $i \in \mathbb{Z}$.

Let G be the group of \mathcal{S} -module automorphisms of V . Thus G is isomorphic to $\mathrm{GL}_r(\mathcal{S})$. G acts on \mathcal{F} with orbits $\{\mathcal{F}_\lambda : \lambda \in \Lambda_0\}$, where Λ_0 is the set of compositions of r into n parts, as in Definition 3.0.1.

The diagonal action of G on $\mathcal{F} \times \mathcal{F}$ has orbits $\{\mathcal{O}_A : A \in \Lambda_1\}$, where \mathcal{O}_A consists of those pairs of flags with periodic characteristic matrix equal to A . Definitions of the periodic characteristic matrix and the set Λ_1 are given in Definition 3.1.1 and Definition 3.0.2 respectively.

Recall that the periodic characteristic matrix of a pair $(L, L') \in \mathcal{F} \times \mathcal{F}$ is the $\mathbb{Z} \times \mathbb{Z}$ matrix $A = (a_{i,j})_{i,j \in \mathbb{Z}}$, with

$$a_{i,j} = \dim \left(\frac{L_i \cap L'_j}{L_{i-1} \cap L'_j + L_i \cap L'_{j-1}} \right)$$

for each $i, j \in \mathbb{Z}$.

Recall that ro and co are the maps $\Lambda_1 \rightarrow \Lambda_0$ given by

$$\mathrm{ro}(A) = \left(\sum_{j \in \mathbb{Z}} a_{1,j}, \dots, \sum_{j \in \mathbb{Z}} a_{n,j} \right)$$

and

$$\mathrm{co}(A) = \left(\sum_{i \in \mathbb{Z}} a_{i,1}, \dots, \sum_{i \in \mathbb{Z}} a_{i,n} \right)$$

for each $A \in \Lambda_1$. Given $A \in \Lambda_1$, write $A: \mathrm{co}(A) \rightarrow \mathrm{ro}(A)$.

The purpose of this chapter is to define an associative \mathbb{Z} -algebra with a multiplicative basis by defining a modified form of the product in the affine q -Schur algebra. In particular, given $A, B \in \Lambda_1$, the orbit product

$$X_{A,B} = \{(L, L'') \in \mathcal{F} \times \mathcal{F} : \exists L' \in \mathcal{F} \text{ with } (L, L') \in \mathcal{O}_A, (L', L'') \in \mathcal{O}_B\}$$

consists of finitely many G -orbits and it will be shown that there is a unique ‘generic’ orbit in $X_{A,B}$, denoted \mathcal{O}_{A*B} , with the property that

$$\dim \left(\frac{L_i}{L_i \cap L_j''} \right) \leq \dim \left(\frac{N_i}{N_i \cap N_j''} \right)$$

and

$$\dim \left(\frac{L_j''}{L_i \cap L_j''} \right) \leq \dim \left(\frac{N_j''}{N_i \cap N_j''} \right)$$

for all $i, j \in \mathbb{Z}$, $(N, N'') \in \mathcal{O}_{A*B}$ and $(L, L'') \in X_{A,B}$. It will be shown that the above ‘generic product’ of orbits is associative, so the free \mathbb{Z} -module on the set of G -orbits in $\mathcal{F} \times \mathcal{F}$ with \mathbb{Z} -bilinear multiplication given by

$$\mathcal{O}_A * \mathcal{O}_B = \mathcal{O}_{A*B},$$

for each $A, B \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$, and

$$\mathcal{O}_A * \mathcal{O}_B = 0$$

for $A, B \in \Lambda_1$ with $\text{co}(A) \neq \text{ro}(B)$, is an associative \mathbb{Z} -algebra with multiplicative identity given by

$$\sum_{\lambda \in \Lambda_0} \mathcal{O}_{D_\lambda},$$

where D_λ is the diagonal matrix with $\text{co}(D_\lambda) = \lambda$. The resulting \mathbb{Z} -algebra is called the *generic affine algebra* (of rank r and period n), denoted $\hat{G}(n, r)$.

5.2 A combinatorial partial order

For each $i, j \in \mathbb{Z}$, let $d_{i,j}$ and $\bar{d}_{i,j}$ be the maps from Λ_1 to Λ_0 given by

$$d_{i,j}(A) = \sum_{s \leq i, t > j} a_{s,t}$$

and

$$\bar{d}_{i,j}(A) = \sum_{s > i, t \leq j} a_{s,t}$$

for each $A \in \Lambda_1$.

Lemma 5.2.1. *For each $A \in \Lambda_1$ and $i, j \in \mathbb{Z}$, the following equations hold:*

$$\begin{aligned} d_{i,j}(A) - d_{i-1,j}(A) &= \sum_{t > j} a_{i,t} \\ d_{i,j}(A) - d_{i,j-1}(A) &= - \sum_{s \leq i} a_{s,j} \end{aligned}$$

and

$$\begin{aligned} \bar{d}_{i,j}(A) - \bar{d}_{i,j-1}(A) &= - \sum_{t \leq j} a_{i,t} \\ \bar{d}_{i,j}(A) - \bar{d}_{i,j-1}(A) &= \sum_{s > i} a_{s,j} \end{aligned}$$

Proof. Let $i, j \in \mathbb{Z}$ and $A \in \Lambda_1$. Then

$$d_{i,j}(A) - d_{i-1,j}(A) = \sum_{s \leq i, t > j} a_{s,t} - \sum_{s \leq i-1, t > j} a_{s,t} = \sum_{t > j} a_{i,t}$$

and

$$d_{i,j}(A) - d_{i,j-1}(A) = \sum_{s \leq i, t > j} a_{s,t} - \sum_{s \leq i, t > j-1} a_{s,t} = - \sum_{s \leq i} a_{s,j}.$$

Similarly,

$$\bar{d}_{i,j}(A) - \bar{d}_{i-1,j}(A) = \sum_{s > i, t \leq j} a_{s,t} - \sum_{s > i-1, t \leq j} a_{s,t} = - \sum_{t \leq j} a_{i,t}$$

and

$$\bar{d}_{i,j}(A) - \bar{d}_{i,j-1}(A) = \sum_{s > i, t \leq j} a_{s,t} - \sum_{s > i, t \leq j-1} a_{s,t} = \sum_{s > i} a_{s,j}.$$

□

Lemma 5.2.2. For each $A \in \Lambda_1$ and $i, j \in \mathbb{Z}$,

$$a_{i,j} = d_{i,j-1}(A) - d_{i-1,j-1}(A) - d_{i,j}(A) + d_{i-1,j}(A)$$

and

$$a_{i,j} = \bar{d}_{i,j-1}(A) - \bar{d}_{i-1,j-1}(A) - \bar{d}_{i,j}(A) + \bar{d}_{i-1,j}(A).$$

Proof. As a result of Lemma 5.2.1,

$$\begin{aligned} d_{i,j-1}(A) - d_{i-1,j-1}(A) - d_{i,j}(A) + d_{i-1,j}(A) &= \sum_{t > j-1} a_{i,t} - \sum_{t > j} a_{i,t} \\ &= a_{i,j} \end{aligned}$$

and

$$\begin{aligned} \bar{d}_{i,j-1}(A) - \bar{d}_{i-1,j-1}(A) - \bar{d}_{i,j}(A) + \bar{d}_{i-1,j}(A) &= - \sum_{t \leq j-1} a_{i,t} + \sum_{t \leq j} a_{i,t} \\ &= a_{i,j}. \end{aligned}$$

□

Define a relation \leq on Λ_1 by $A \leq B$ if and only if the following conditions are satisfied:

- $\text{ro}(A) = \text{ro}(B)$ and $\text{co}(A) = \text{co}(B)$.
- For each $i, j \in \mathbb{Z}$, $d_{i,j}(A) \leq d_{i,j}(B)$.
- For each $i, j \in \mathbb{Z}$, $\bar{d}_{i,j}(A) \leq \bar{d}_{i,j}(B)$.

Lemma 5.2.3. The relation \leq defines a partial order on Λ_1 .

Proof. It is clear that \leq is reflexive and transitive.

Suppose $A, B \in \Lambda_1$ with $A \leq B$ and $B \leq A$. Then $d_{i,j}(A) = d_{i,j}(B)$ for each $i, j \in \mathbb{Z}$ with $i \leq j$, which shows $a_{s,t} = b_{s,t}$ whenever $s < t$, as a result of Lemma 5.2.2. Similarly, $\bar{d}_{i,j}(A) = \bar{d}_{i,j}(B)$ for each $i, j \in \mathbb{Z}$ with $i \geq j$, so $a_{s,t} = b_{s,t}$ whenever $s > t$. Moreover, $a_{i,i} = b_{i,i}$ for each $i \in \mathbb{Z}$, since $\text{co}(A) = \text{co}(B)$. Thus $A = B$, which shows \leq is antisymmetric and therefore \leq is a partial order on Λ_1 . □

Lemma 5.2.4. *The transpose operation on Λ_1 is order preserving. In particular, $B \leq A$ if and only if $B^\top \leq A^\top$.*

Proof. Suppose $A, B \in \Lambda_1$ with $B \leq A$. The condition $\text{co}(A) = \text{co}(B)$ and $\text{ro}(A) = \text{ro}(B)$ is preserved by the transpose operation.

For each $i, j \in \mathbb{Z}$,

$$d_{i,j}(A^\top) = \sum_{s \leq i, t > j} a_{t,s} = \bar{d}_{j,i}(A)$$

and

$$\bar{d}_{i,j}(A^\top) = \sum_{s > i, t \leq j} a_{t,s} = d_{j,i}(A).$$

It follows that $B^\top \leq A^\top$ and therefore the transpose is order preserving. \square

The partial order on Λ_1 induces a partial order on the set of G -orbits in $\mathcal{F} \times \mathcal{F}$, such that $\mathcal{O}_A \leq \mathcal{O}_B$ if and only if $A \leq B$. The following lemma is rephrased from Lemma 3.1.4 and gives some geometric significance to the partial order on Λ_1 .

Lemma 5.2.5. *Let $A \in \Lambda_1$ and $(L, L') \in \mathcal{O}_A$. Then*

$$\dim \left(\frac{L_i}{L_i \cap L'_j} \right) = d_{i,j}(A)$$

and

$$\dim \left(\frac{L'_j}{L_i \cap L'_j} \right) = \bar{d}_{i,j}(A),$$

for each $i, j \in \mathbb{Z}$.

Proof. This is a rephrasing of Lemma 3.1.4. \square

5.3 Grassmannians and related varieties

Here we collect a few elementary results on Grassmannians and some related varieties. In this section, let V be an n -dimensional \mathbf{k} -vector space and let $0 \leq d \leq n$ be an integer. There is a linear map

$$\phi^{(d)}: \Lambda^d(V) \rightarrow \text{Hom}(V, \Lambda^{d+1}(V))$$

given by

$$\phi^{(d)}(\alpha)(v) = \alpha \wedge v$$

for $\alpha \in \Lambda^d(V)$ and $v \in V$. The kernel of $\phi^{(d)}(\alpha)$ is the space of divisors of α ,

$$D_\alpha = \{v \in V : \alpha \wedge v = 0\}.$$

An element $\alpha \in \Lambda^d(V)$ is said to be totally decomposable if $\alpha = \alpha_1 \wedge \cdots \wedge \alpha_d$, where $\alpha_1, \dots, \alpha_d \in V$ are linearly independent. The dimension of D_α is at most d and $\dim(D_\alpha) = d$ precisely when α is totally decomposable. Consequently, the rank of $\phi^{(d)}(\alpha)$ is at least $n - d$ and α is totally decomposable if and only if $\text{rank } \phi^{(d)}(\alpha) \leq n - d$, which holds if and only if the $(n - d + 1) \times (n - d + 1)$ -minors of a matrix of $\phi^{(d)}(\alpha)$ are all zero.

Lemma 5.3.1. $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap U_2) \geq a\}$ is a projective variety, for each $d_1, d_2, a \in \mathbb{N}$ with $d_1, d_2, a \leq n$.

Proof. As above, there is a linear map $\Psi: \Lambda^{d_1}V \oplus \Lambda^{d_2}V \rightarrow \text{Hom}(V, \Lambda^{d_1+1}(V) \oplus \Lambda^{d_2+1}(V))$ given by $\Psi(\alpha, \beta)(v) = (\alpha \wedge v, \beta \wedge v)$. Given $\alpha \in \Lambda^{d_1}(V)$ and $\beta \in \Lambda^{d_2}(V)$, the kernel of $\Psi(\alpha, \beta)$ is $D_\alpha \cap D_\beta$ and so the rank of $\Psi(\alpha, \beta)$ is $n - \dim(D_\alpha \cap D_\beta)$.

Let $U_i \in \text{Gr}_{d_i}(V)$ and suppose $p_i(U_i) = [\alpha_i]$, where p_i is the Plücker embedding of $\text{Gr}_{d_i}(V)$ in $\mathbb{P}(\Lambda^{d_i}(V))$, so $U_i = D_{\alpha_i} = \ker \phi^{(d_i)}(\alpha_i)$. Therefore the kernel of $\Psi(\alpha_1, \alpha_2)$ is $U_1 \cap U_2$, so the condition that $\dim(U_1 \cap U_2) \geq a$ is equivalent to the condition that $\Psi(\alpha_1, \alpha_2)$ has rank at most $n - a$. After fixing a basis of V , this condition is given by the vanishing of the $(n - a + 1) \times (n - a + 1)$ minors of the matrix of $\Psi(\alpha_1, \alpha_2)$ with respect to this basis. Therefore $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap U_2) \geq a\}$ is a closed subset of the product of Grassmannians $\text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V)$, so is a projective variety.

More precisely, the entries of a matrix of $\Psi(\alpha_1, \alpha_2)$ are homogeneous polynomials of degree 1 in the Plücker coordinates on $\text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V)$ since Ψ is linear and so the minors of $\Psi(\alpha_1, \alpha_2)$ are also homogeneous polynomials in the Plücker coordinates. \square

Lemma 5.3.2. Let V be an n -dimensional vector space over \mathbf{k} and let $d_1, d_2, a \in \mathbb{N}$ with $d_1, d_2, a \leq n$. The following hold:

1. $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap U_2) = a\}$ is a quasiprojective variety;
2. $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : U_1 \subset U_2\}$ is a projective variety;
3. Given $U_2 \in \text{Gr}_{d_2}(V)$, $\{U_1 \in \text{Gr}_{d_1}(V) : \dim(U_1 \cap U_2) \geq a\}$ is a projective variety;
4. Given $U_2 \in \text{Gr}_{d_2}(V)$, $\{U_1 \in \text{Gr}_{d_1}(V) : \dim(U_1 \cap U_2) = a\}$ is a quasiprojective variety;
5. Given $U_2 \in \text{Gr}_{d_2}(V)$, $\{U_1 \in \text{Gr}_{d_1}(V) : U_1 \subset U_2\}$ is a projective variety;
6. Given $U_2 \in \text{Gr}_{d_2}(V)$, $\{U_1 \in \text{Gr}_{d_1}(V) : U_2 \subset U_1\}$ is a projective variety.

Proof. Let X_i denote the space in statement i of the lemma. To emphasise the dependence of X_i on a , write $X_{i,a}$.

X_1 is a quasiprojective variety since it is equal to the intersection of the projective variety $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap U_2) \geq a\}$ with the open set $\{(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap U_2) \leq a\}$.

Given $(U_1, U_2) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V)$, $U_1 \subset U_2$ if and only if $\dim(U_1 \cap U_2) \geq d_1$, so Lemma 5.3.1 shows X_2 is a projective variety.

Let $\pi_i: \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) \rightarrow \text{Gr}_{d_i}(V)$ be the projection map onto the i -th factor, for $i = 1, 2$. The completeness property of projective varieties ensures that π_i is a closed morphism. Observe that

$$\begin{aligned} X_3 &= \{U_1 \in \text{Gr}_{d_1}(V) : \dim(U_1 \cap U_2) \geq a\} \\ &= \pi_1(\{(U_1, W) \in \text{Gr}_{d_1}(V) \times \text{Gr}_{d_2}(V) : \dim(U_1 \cap W) \geq a\} \cap \pi_2^{-1}\{U_2\}). \end{aligned}$$

The fibre of π_2 over U_2 is closed, so the intersection of the fibre with the variety from Lemma 5.3.1 is closed and then the image of this intersection under π_1 is closed. This shows X_3 is a projective variety.

X_4 is a quasiprojective variety since it is the complement of the subvariety $X_{3,a+1}$ in $X_{3,a}$. Finally, 5-6 follow as special cases of 3 since $X_5 = X_{3,d_1}$ and $X_6 = X_{3,d_2}$. \square

5.4 Geometry of affine flag varieties

Given $L \in \mathcal{F}$, $N, a \in \mathbb{N}$ and $\lambda \in \Lambda_0$ define

$$\Pi_{N,\lambda}(L) = \{L' \in \mathcal{F}_\lambda : \varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0\}.$$

and

$$\Pi_{N,\lambda}^a(L) = \left\{ L' \in \mathcal{F}_\lambda : \varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0, \dim \left(\frac{\varepsilon^{-N} L_0}{L'_0} \right) = a \right\}.$$

Lemma 5.4.1. *Given $L \in \mathcal{F}$, $N \in \mathbb{N}$ and $\lambda \in \Lambda_0$,*

$$\Pi_{N,\lambda}(L) = \bigcup_{a: 0 \leq a \leq 2Nr} \Pi_{N,\lambda}^a(L).$$

Proof. If $L' \in \Pi_{N,\lambda}(L)$ then $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0$ and the $\mathbf{k}[\varepsilon]$ -module $\varepsilon^{-N} L_0 / L'_0$ is naturally isomorphic to $(\varepsilon^{-N} L_0 / \varepsilon^N L_0) / (L'_0 / \varepsilon^N L_0)$, so

$$\dim_{\mathbf{k}} \left(\frac{\varepsilon^{-N} L_0}{L'_0} \right) \leq \dim_{\mathbf{k}} \left(\frac{\varepsilon^{-N} L_0}{\varepsilon^N L_0} \right) = 2Nr.$$

□

Lemma 5.4.2. *Given $L \in \mathcal{F}$, $N \in \mathbb{N}$, $\lambda \in \Lambda_0$ and $a \in \mathbb{N}$ with $0 \leq a \leq 2Nr$, $\Pi_{N,\lambda}^a(L)$ is a projective algebraic variety.*

Proof. Let W be the $\mathbf{k}[\varepsilon]$ -module $\varepsilon^{-1-N} L_0 / \varepsilon^N L_0$, which has dimension $(2N+1)r$ over \mathbf{k} . Let $d_i = 2Nr - a + \lambda_1 + \dots + \lambda_i$ for each $i = 1, \dots, n$. The correspondence between submodules of $\varepsilon^{-1-N} L_0$ which contain $\varepsilon^N L_0$ and submodules of $\varepsilon^{-1-N} L_0 / \varepsilon^N L_0$ determines a map

$$\rho: \Pi_{N,\lambda}^a(L) \rightarrow \mathrm{Gr}_{d_1}(W) \times \dots \times \mathrm{Gr}_{d_n}(W),$$

with $\rho(L') = (L'_1 / \varepsilon^N L_0, \dots, L'_n / \varepsilon^N L_0)$.

Let \mathcal{X} be the space of $(U_1, \dots, U_n) \in \mathrm{Gr}_{d_1}(W) \times \dots \times \mathrm{Gr}_{d_n}(W)$ with $U_i \subset U_{i+1}$ for $i = 1, \dots, n-1$ and $\varepsilon U_n \subset U_1$. Lemma 5.3.2 shows that each of these conditions is closed, so \mathcal{X} is a closed subset of $\mathrm{Gr}_{d_1}(W) \times \dots \times \mathrm{Gr}_{d_n}(W)$, therefore \mathcal{X} is a projective algebraic variety.

The image of ρ is contained in \mathcal{X} since

$$\varepsilon L'_n / \varepsilon^N L_0 = L'_0 / \varepsilon^N L_0 \subset L'_1 / \varepsilon^N L_0 \subset \dots \subset L'_n / \varepsilon^N L_0.$$

Suppose $(U_1, \dots, U_n) \in \mathcal{X}$. Then U_i is a $\mathbf{k}[\varepsilon]$ -module, since $\varepsilon U_i \subset \varepsilon U_n \subset U_1 \subset U_i$, for each $i = 1, \dots, n$, so U_i lifts uniquely to a $\mathbf{k}[\varepsilon]$ -module L'_i with $\varepsilon^N L_0 \subset L'_i \subset \varepsilon^{-1-N} L_0$. Therefore L'_1, \dots, L'_n are $\mathbf{k}[\varepsilon]$ -lattices with $L_i \subset L_{i+1}$ for $i = 1, \dots, n-1$ and $\varepsilon L'_n \subset L'_1$, with

$$\dim(\varepsilon^{-1-N} L_0 / L'_n) = \dim(W / W_n) = (2N+1)r - d_n = a$$

and

$$\dim(L'_i / L'_{i-1}) = \dim(W_i / W_{i-1}) = d_i - d_{i-1} = \lambda_i,$$

for each $i = 2, \dots, n$. Therefore there is a unique $L' \in \Pi_{N,\lambda}^a(L)$ such that $\rho(L') = (W_1, \dots, W_n)$, where L' is given by $L'_{i+cn} = \varepsilon^{-c} L'_i$ for $i = 1, \dots, n$ and $c \in \mathbb{Z}$. It follows ρ is injective and $\mathrm{im} \rho = \mathcal{X}$, which is a projective variety, so $\Pi_{N,\lambda}^a(L)$ is a projective variety. □

Lemma 5.4.3. *Given $L \in \mathcal{F}$, $N \in \mathbb{N}$, $\lambda \in \Lambda_0$ and $a \in \mathbb{N}$ with $0 \leq a \leq 2Nr$, $\Pi_{N,\lambda}^a(L)$ is closed in $\Pi_{N+1,\lambda}^{a+r}(L)$.*

Proof. If $L' \in \Pi_{N,\lambda}^a(L)$, then $\varepsilon^{N+1}L_0 \subset \varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N}L_0 \subset \varepsilon^{-(N+1)}L_0$ and

$$\dim \left(\frac{\varepsilon^{-(1+n)}L_0}{L'_0} \right) = \dim \left(\frac{L_0}{\varepsilon L_0} \right) + \dim \left(\frac{\varepsilon^{-N}L_0}{L'_0} \right) = r + a,$$

which shows that $\Pi_{N,\lambda}^a(L) \subset \Pi_{N+1,\lambda}^{a+r}(L)$. For $L' \in \Pi_{N+1,\lambda}^{a+r}(L)$, if additionally $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N}L_0$, then

$$\dim \left(\frac{\varepsilon^{-(N+1)}L_0}{L'_0} \right) = r + \dim \left(\frac{\varepsilon^{-N}L_0}{L'_0} \right),$$

which shows $L' \in \Pi_{N,\lambda}^a(L)$. Therefore $\Pi_{N,\lambda}^a(L)$ is the subspace of $\Pi_{N+1,\lambda}^{a+r}(L)$ defined by the two closed conditions $\varepsilon^N L_0 \subset L'_0$ and $L'_0 \subset \varepsilon^{-N}L_0$, using Lemma 5.3.2. \square

Lemma 5.4.4. *Let $\lambda \in \Lambda_0$, $M, N \in \mathbb{N}$, $L, \tilde{L} \in \mathcal{F}$, $0 \leq a \leq 2Nr$, $0 \leq b \leq 2Mr$. $\Pi_{N,\lambda}^a(L) \cap \Pi_{M,\lambda}^b(\tilde{L})$ is a closed set in $\Pi_{N,\lambda}^a(L)$. In particular, if the intersection is nonempty it is a projective algebraic variety.*

Proof. Observe that $\Pi_{N,\lambda}^a(L) \cap \Pi_{M,\lambda}^b(\tilde{L})$ is the subset of $\Pi_{N,\lambda}^a(L)$ defined by the additional conditions that $\varepsilon^M \tilde{L}_0 \subset L'_0$ and $L'_0 \subset \varepsilon^{-M} \tilde{L}_0$, so is a closed subset of $\Pi_{N,\lambda}^a(L)$, using 5.3.2. \square

Lemma 5.4.5. *Suppose $L \in \mathcal{F}$, $N, a \in \mathbb{N}$ and $\lambda \in \Lambda_0$ with $a \leq 2Nr$. For each $g \in G$, the natural map (restriction of the action map) $\Pi_{N,\lambda}^a(L) \rightarrow \Pi_{N,\lambda}^a(gL)$ is an isomorphism of projective varieties.*

Proof. If $L' \in \Pi_{N,\lambda}^a(L)$, then $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N}L_0$ and so $\varepsilon^N g(L_0) \subset g(L'_0) \subset \varepsilon^{-N}g(L_0)$, so $gL' \in \Pi_{N,\lambda}^a(gL)$. Thus g and g^{-1} induce mutually inverse morphisms of varieties $g: \Pi_{N,\lambda}^a(L) \rightarrow \Pi_{N,\lambda}^a(gL)$ and $g^{-1}: \Pi_{N,\lambda}^a(gL) \rightarrow \Pi_{N,\lambda}^a(L)$. \square

5.4.1 Action through an algebraic group

Let W be the $\mathbb{C}[\varepsilon]$ -module $\varepsilon^{-(1+N)}L_0/\varepsilon^N L_0$. ε^{2N+1} acts as zero on W and $\mathbb{C}[\varepsilon]/\langle \varepsilon^{2N+1} \rangle \otimes_{\mathbb{C}[\varepsilon]} W$ is a free $\mathbb{C}[\varepsilon]/\langle \varepsilon^{2N+1} \rangle$ -module of rank r . In particular, W is a complex vector space of dimension $(2N+1)r$.

Each element $g \in G_L$ determines an endomorphism \bar{g} of W , given by

$$\bar{g}(x + \varepsilon^N L_0) = g(x) + \varepsilon^N L_0,$$

for each $x \in \varepsilon^{-(1+N)}L_0$. Given $g, h \in G_L$, $\overline{gh} = \bar{g}\bar{h}$ and so \bar{g} is an automorphism of W with $\bar{g}^{-1} = \overline{g^{-1}}$. Therefore the map $\bar{\cdot}: G_L \mapsto \text{GL}(W)$ given by $g \mapsto \bar{g}$ is a group homomorphism with kernel

$$H_{N,L} := \{g \in G_L : \bar{g} = 1\},$$

which consists of those $g \in G_L$ such that

$$g(x) - x \in \varepsilon^N L_0$$

for each $x \in \varepsilon^{-(1+N)}L_0$. Thus $G_L/H_{N,L}$ may be identified with a subgroup of $\text{GL}(W)$.

Lemma 5.4.6. $G_L/H_{N,L}$ is a connected algebraic group.

Proof. As a result of the first isomorphism theorem, $G_L/H_{N,L}$ is isomorphic to the image of G_L in $\mathrm{GL}(W)$, which will be described explicitly by equations in the coordinate functions on $\mathrm{GL}(W)$, with respect to a fixed basis of W .

Let $\{\tilde{x}_1, \dots, \tilde{x}_r\}$ be a basis of L_n/L_0 over \mathbb{C} which is adapted to the flag

$$L_1/L_0 \subset \dots \subset L_{n-1}/L_0 \subset L_n/L_0,$$

so that

$$L_i/L_0 = \langle \tilde{x}_1, \dots, \tilde{x}_{\lambda_1 + \dots + \lambda_i} \rangle$$

for each $i \in \{1, \dots, n\}$. Fix $x_1, \dots, x_r \in L_n$ such that $\tilde{x}_i = x_i + L_0$ for each $i = 1, \dots, r$, then

$$L_i = L_0 + \langle x_1, \dots, x_{\lambda_1 + \dots + \lambda_i} \rangle$$

for $i = 1, \dots, r$.

Then W has a \mathbb{C} -basis $\{y_j : 1 \leq j \leq (2N+1)r\}$ given by

$$y_{i+cr} = \varepsilon^{-c+N} x_i$$

for each $i \in \{1, \dots, r\}$ and $c \in \{0, \dots, 2N\}$. Observe that $\varepsilon y_i = 0$ for $i \in \{1, \dots, r\}$ and $\varepsilon y_i = y_{i-r}$ for $r < i \leq (2N+1)r$.

The coordinate functions on $\mathrm{GL}(W)$ with respect to this choice of basis are the maps

$$\gamma_{i,j} : \mathrm{GL}(W) \rightarrow \mathbb{C}$$

for $i, j \in \mathbb{Z}$ with $1 \leq i, j \leq (2N+1)r$, given by

$$g(y_j) = \sum_i \gamma_{ij}(g) y_i,$$

for each $j = 1, \dots, (2N+1)r$.

The image of G_L in $\mathrm{GL}(W)$ is the subgroup defined by the conditions

$$\gamma_{i,j} = \gamma_{i-r,j-r}$$

for each $i, j \in \{r+1, \dots, (2N+1)r\}$ and

$$\gamma_{i,j} = 0$$

for each $i, j \in \{1, \dots, (2N+1)r\}$ with $i > \lambda_1 + \dots + \lambda_s$ and $j \leq \lambda_1 + \dots + \lambda_s$ for some $s \in \{1, \dots, r\}$. This shows that the image of G_L in $\mathrm{GL}(W)$ is a connected algebraic group and therefore $G_L/H_{N,L}$ is a connected algebraic group.

With respect to the basis $\{y_i : i \in \{1, \dots, (2N+1)r\}\}$, the image of G_L in $\mathrm{GL}(W)$ consists of matrices of the form

$$\begin{pmatrix} A_0 & A_1 & A_2 & \cdots & A_{2N} \\ 0 & A_0 & A_1 & \cdots & A_{2N-1} \\ 0 & 0 & A_0 & \cdots & A_{2N-2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & A_0 \end{pmatrix}$$

where $A_0 \in \mathcal{P}_\lambda$ and $A_1, \dots, A_{2N} \in M_r(\mathbb{C})$, where \mathcal{P}_λ is the parabolic subgroup of $\mathrm{GL}_r(\mathbb{C})$ which is the stabiliser of the flag

$$L_1/L_0 \subset \dots \subset L_{n-1}/L_0 \subset L_n/L_0.$$

□

Given $g \in G$, the map $G_L \rightarrow G_{gL}$ sending h to ghg^{-1} is a group isomorphism which descends to an isomorphism of algebraic groups $G_L/H_{N,L} \rightarrow G_{gL}/H_{N,gL}$. Thus we have a commuting diagram of morphisms of varieties, where the vertical arrows are isomorphisms:

$$\begin{array}{ccc} G_L/H_{N,L} \times \Pi_{N,\lambda}^a(L) & \longrightarrow & \Pi_{N,\lambda}^a(L) \\ \downarrow & & \downarrow \\ G_{gL}/H_{N,gL} \times \Pi_{N,\lambda}^a(gL) & \longrightarrow & \Pi_{N,\lambda}^a(gL) \end{array}$$

5.4.2 Incidence in affine flag varieties

Lemma 5.4.7. *Given $N, a, b, c \in \mathbb{N}$, $\lambda, \mu \in \Lambda_0$, $L \in \mathcal{F}$ and $i, j \in \mathbb{Z}$,*

$$\left\{ (L', L'') \in \Pi_{N,\lambda}^a(L) \times \Pi_{N,\mu}^b(L) : \dim \left(\frac{L'_i}{L'_i \cap L''_j} \right) \leq c \right\}$$

is a closed set in the projective variety $\Pi_{N,\lambda}^a(L) \times \Pi_{N,\mu}^b(L)$.

Proof. There is $M \geq N$ so that $\varepsilon^M L_0 \subset L'_i \subset \varepsilon^{-M} L_0$ and $\varepsilon^M L_0 \subset L''_j \subset \varepsilon^{-M} L_0$. Let $a' = a + (M - N)r$ and $b' = b + (M - N)r$. Lemma 5.4.3 shows that $\Pi_{N,\lambda}^a(L)$ is a subvariety of $\Pi_{M,\lambda}^{a'}(L)$, so $\Pi_{N,\lambda}^a(L) \times \Pi_{N,\mu}^b(L)$ is a subvariety of $\Pi_{M,\lambda}^{a'}(L) \times \Pi_{M,\mu}^{b'}(L)$.

The fact that

$$\dim \left(\frac{L'_i}{L'_i \cap L''_j} \right) = \dim \left(\frac{L'_i/\varepsilon^M L_0}{L'_i/\varepsilon^M L_0 \cap L''_j/\varepsilon^M L_0} \right),$$

together with Lemma 5.4.2 and Lemma 5.3.1, shows that

$$\left\{ (L', L'') \in \Pi_{M,\lambda}^{a'}(L) \times \Pi_{M,\mu}^{b'}(L) : \dim \left(\frac{L'_i}{L'_i \cap L''_j} \right) \leq c \right\}$$

is closed, so the intersection with $\Pi_{N,\lambda}^a(L) \times \Pi_{N,\mu}^b(L)$ is closed. □

Lemma 5.4.8. *Given $N, a, c \in \mathbb{N}$, $\lambda \in \Lambda_0$, $L \in \mathcal{F}$ and $i, j \in \mathbb{Z}$,*

$$\left\{ L' \in \Pi_{N,\lambda}^a(L) : \dim \left(\frac{L_i}{L_i \cap L'_j} \right) \leq c \right\}$$

and

$$\left\{ L' \in \Pi_{N,\lambda}^a(L) : \dim \left(\frac{L'_j}{L_i \cap L'_j} \right) \leq c \right\}$$

are closed sets in $\Pi_{N,\lambda}^a(L)$.

Proof. This is a result of Lemma 5.3.2, since

$$\dim \left(\frac{L_i}{L_i \cap L'_j} \right) = \dim \left(\frac{L_i/\varepsilon^M L_0}{L_i/\varepsilon^M L_0 \cap L'_j/\varepsilon^M L_0} \right),$$

where $M \geq N$ is chosen so that $\varepsilon^M L_0 \subset L_i \subset \varepsilon^{-M} L_0$ and $\varepsilon^M L_0 \subset L'_j \subset \varepsilon^{-M} L_0$ for each $L' \in \Pi_{N,\lambda}^a(L)$. □

5.5 Geometry of orbits

Let $A \in \Lambda_1$ and $L \in \mathcal{F}_{\text{ro}(A)}$ and write $\lambda = \text{co}(A)$. Recall that

$$X_A^L = \{L' \in \mathcal{F}_\lambda : (L, L') \in \mathcal{O}_A\}.$$

Lemma 5.5.1. *There is $N \in \mathbb{N}$ such that $X_A^L \subset \Pi_{N,\lambda}^a(L)$, where $a = d_{nN,0}A$.*

Proof. There is $N \in \mathbb{N}$ so that $a_{i,j} = 0$ whenever $|j - i| > nN$. If $(L, L') \in \mathcal{O}_A$ then

$$\dim \left(\frac{L'_0}{L'_0 \cap \varepsilon^{-N} L_0} \right) = \dim \left(\frac{L'_0}{L'_0 \cap L_{nN}} \right) = \sum_{s > nN, t \leq 0} a_{s,t} = 0,$$

so it follows $L'_0 \subset \varepsilon^{-N} L_0$. Similarly,

$$\dim \left(\frac{\varepsilon^N L_0}{\varepsilon^N L_0 \cap L'_0} \right) = \dim \left(\frac{L_{-nN}}{L_{-nN} \cap L'_0} \right) = \sum_{s \leq -nN, t > 0} a_{s,t} = 0,$$

which shows $\varepsilon^N L_0 \subset L'_0$. Moreover,

$$\dim \left(\frac{\varepsilon^{-N} L_0}{L'_0} \right) = \dim \left(\frac{\varepsilon^{-N} L_0}{\varepsilon^{-N} L_0 \cap L'_0} \right) = \sum_{s \leq nN, t > 0} a_{s,t} = d_{nN,0}(A),$$

as a result of Lemma 5.2.5. □

Assume $N \in \mathbb{N}$ is chosen so that $X_A^L \subset \Pi_{N,\lambda}^a(L)$, where $a = d_{nN,0}A$, as in Lemma 5.5.1.

Lemma 5.5.2. *X_A^L is a locally closed subset of $\Pi_{N,\lambda}^a(L)$. In particular, X_A^L is a quasiprojective variety.*

Proof. If $L' \in \Pi_{N,\lambda}^a(L)$ then

$$L_{-Nn} = \varepsilon^N L_0 \subset L'_0 \subset L'_1 \subset L'_n \subset \varepsilon^{-1-N} L_0 = L_{(N+1)n}.$$

Therefore X_A^L is the subset of $\Pi_{N,\lambda}^a(L)$ defined by the conditions $\dim(L_i/L_i \cap L'_j) = d_{i,j}A$ for $i : -Nn \leq i < j$ and $\dim(L'_j/L_i \cap L'_j) = \bar{d}_{i,j}A$ for $i : j < i \leq (N+1)n$, for $j = 1, \dots, n$.

The set of $L' \in \Pi_{N,\lambda}^a(L)$ with $\dim(L_i/L_i \cap L'_j) \leq d_{i,j}A$ for $j = 1, \dots, n$ and $i : -Nn \leq i < j$ and $\dim(L'_j/L_i \cap L'_j) \leq \bar{d}_{i,j}A$ for $j = 1, \dots, n$ and $i : j < i \leq (N+1)n$ is a closed subset of $\Pi_{N,\lambda}^a(L)$, as a result of Lemma 5.4.8.

On the other hand, the set of $L' \in \Pi_{N,\lambda}^a(L)$ satisfying the conditions $\dim(L_i/L_i \cap L'_j) \geq d_{i,j}A$ (for $i < j$) and $\dim(L'_j/L_i \cap L'_j) \geq \bar{d}_{i,j}A$ (for $i > j$) is open in $\Pi_{N,\lambda}^a(L)$ since the complement is closed, as a result of Lemma 5.4.8.

Therefore X_A^L is the intersection of an open set and a closed set in $\Pi_{N,\lambda}^a(L)$, so X_A^L is locally closed. It follows that X_A^L is an open subset of the projective variety $\overline{X_A^L}$, so is a quasiprojective variety as claimed. □

Lemma 5.5.3. *X_A^L is irreducible.*

Proof. For any $L' \in X_A^L$, $X_A^L = G_L/H_{N,L} \cdot L'$. Lemma 5.4.6 shows that $G_L/H_{N,L}$ is a connected algebraic group which acts algebraically on $\Pi_{N,\lambda}^a(L)$. The image of $G_L/H_{N,L}$ under the morphism $g \mapsto gL'$ equals X_A^L , which shows X_A^L is irreducible since $G_L/H_{N,L}$ is irreducible. □

Consequently, $\overline{X_A^L}$ is an irreducible projective variety and the action of $G_L/H_{N,L}$ on $\Pi_{N,\lambda}^a(L)$ restricts to an algebraic group action on $\overline{X_A^L}$ for which there are finitely many orbits. In particular, $\overline{X_A^L} \setminus X_A^L$ is a union of finitely many orbits which are so-called degenerations of the orbit X_A^L .

5.6 Geometry of orbit products

Let $A, B \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$ and write $\lambda = \text{co}(A)$ and $\mu = \text{co}(B)$. Fix $L \in \mathcal{F}_{\text{ro}(A)}$. Recall

$$Y_{A,B}^L = \{(L', L'') \in \mathcal{F}_\lambda \times \mathcal{F}_\mu : L' \in X_A^L, L'' \in X_B^{L'}\}$$

and

$$X_{A,B}^L = \{L'' \in \mathcal{F}_\mu : \exists L' \in X_A^L \text{ with } L'' \in X_B^{L'}\}$$

Lemma 5.6.1. *There is $N \in \mathbb{N}$ such that*

$$Y_{A,B}^L \subset \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L),$$

where $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$.

Proof. There is $N \in \mathbb{N}$ such that $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0$ and $\varepsilon^N L'_0 \subset L''_0 \subset \varepsilon^{-N} L'_0$ for each $(L', L'') \in Y_{A,B}^L$, using Lemma 5.5.1. Set $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$.

Then for any $(L', L'') \in Y_{A,B}^L$,

$$\varepsilon^{2N} L_0 \subset \varepsilon^N L'_0 \subset L''_0 \subset \varepsilon^{-N} L'_0 \subset \varepsilon^{-2N} L_0$$

and

$$\begin{aligned} \dim \left(\frac{\varepsilon^{-2N} L_0}{L''_0} \right) &= \dim \left(\frac{\varepsilon^{-N} L'_0}{L''_0} \right) + \dim \left(\frac{\varepsilon^{-2N} L_0}{\varepsilon^{-N} L'_0} \right) \\ &= \dim \left(\frac{\varepsilon^{-N} L'_0}{L''_0} \right) + \dim \left(\frac{\varepsilon^{-N} L_0}{L'_0} \right) \\ &= a + b, \end{aligned}$$

as a result of Lemma 5.2.5, so $(L', L'') \in \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$ as required. \square

Now assume $N \in \mathbb{N}$ is chosen so that $Y_{A,B}^L \subset \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$, where $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$, using Lemma 5.6.1.

Lemma 5.6.2. *$Y_{A,B}^L$ is a locally closed subset of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$. In particular, $Y_{A,B}^L$ is a quasiprojective variety.*

Proof. $Y_{A,B}^L$ is the subset of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$ consisting of those (L', L'') satisfying the following conditions: $\dim(L_i/L_i \cap L'_j) = d_{i,j}(A)$ for $i < j$, $\dim(L'_j/L_i \cap L'_j) = \bar{d}_{i,j}(A)$ for $i > j$, $\dim(L'_i/L'_i \cap L''_j) = d_{i,j}(B)$ for $i < j$ and $\dim(L''_j/L'_i \cap L''_j) = \bar{d}_{i,j}(B)$. Only finitely many conditions are required to define $Y_{A,B}^L$ since there are only finitely many nonzero entries in A and B modulo the (n, n) -periodicity.

The conditions $\dim(L_i/L_i \cap L'_j) \leq d_{i,j}(A)$, $\dim(L'_j/L'_i \cap L''_j) \leq d_{i,j}(B)$, $\dim(L'_j/L_i \cap L'_j) \leq \bar{d}_{i,j}(A)$ and $\dim(L''_j/L'_i \cap L''_j) \leq \bar{d}_{i,j}(B)$ define closed subsets of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$ for each $i, j \in \mathbb{Z}$, as a result of Lemma 5.4.7 and Lemma 5.4.8.

On the other hand, the conditions $\dim(L_i/L_i \cap L'_j) \geq d_{i,j}(A)$, $\dim(L'_j/L'_i \cap L''_j) \geq d_{i,j}(B)$, $\dim(L'_j/L_i \cap L'_j) \geq \bar{d}_{i,j}(A)$ and $\dim(L''_j/L'_i \cap L''_j) \geq \bar{d}_{i,j}(B)$ define open subsets of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$ for each $i, j \in \mathbb{Z}$, using Lemma 5.4.7 and Lemma 5.4.8.

Therefore $Y_{A,B}^L$ is the intersection of finitely many open sets and finitely many closed sets in $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$, so $Y_{A,B}^L$ is locally closed. In particular, $Y_{A,B}^L$ is a quasiprojective variety. \square

Lemma 5.6.3. *For any $L' \in X_A^L$, $Y_{A,B}^L = G_L \cdot (\{L'\} \times X_B^{L'})$.*

Proof. Let $L' \in X_A^L$, then $\{L'\} \times X_B^{L'}$ is contained in $Y_{A,B}^L$ and G_L acts on $Y_{A,B}^L$, so $G_L \cdot (\{L'\} \times X_B^{L'})$ is contained in $Y_{A,B}^L$. If $(N', N'') \in Y_{A,B}^L$, then $N' = \sigma L'$ for some $\sigma \in G_L$, since $N' \in X_A^L$. Then $(N', N'') = \sigma(L', \sigma^{-1}N'')$ and $\sigma^{-1}N'' \in X_B^{\sigma^{-1}N'} = X_B^{L'}$, so $(N', N'') \in \sigma \cdot (\{L'\} \times X_B^{L'})$. Therefore $Y_{A,B}^L = G_L \cdot (\{L'\} \times X_B^{L'})$ as claimed. \square

Proposition 5.6.4. *$Y_{A,B}^L$ is irreducible.*

Proof. Let $L' \in X_A^L$. $G_L/H_{2N,L}$ is a connected algebraic group acting algebraically on $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$ by Lemma 5.4.6. $X_B^{L'}$ is an irreducible locally closed subset of $\Pi_{2N,\mu}^{a+b}(L)$, so $\{L'\} \times X_B^{L'}$ is an irreducible locally closed set in $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L)$. $Y_{A,B}^L = G_L \cdot (\{L'\} \times X_B^{L'}) = G_L/H_{2N,L} \cdot (\{L'\} \times X_B^{L'})$, by Lemma 5.6.3, so it follows that $Y_{A,B}^L$ is irreducible. \square

Let p_2 be the projection onto the second factor $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \rightarrow \Pi_{2N,\mu}^{a+b}(L)$. p_2 is a closed morphism since $\Pi_{N,\lambda}^a(L)$ is a projective variety and therefore complete, by Lemma 5.4.2. Therefore $p_2(\overline{Y_{A,B}^L}) = \overline{X_{A,B}^L}$, since $p_2(Y_{A,B}^L) = X_{A,B}^L$.

Lemma 5.6.5. *$X_{A,B}^L$ is irreducible and constructible.*

Proof. Proposition 5.6.4 shows that $Y_{A,B}^L$ is irreducible and locally closed, so it follows $X_{A,B}^L$ is irreducible and constructible, since $X_{A,B}^L = p_2(Y_{A,B}^L)$. \square

Proposition 5.6.6. *There is a unique open G_L -orbit in $X_{A,B}^L$.*

Proof. $X_{A,B}^L$ consists of finitely many G_L -orbits and is an irreducible topological space, by Lemma 5.6.5. Consequently, X_C^L is dense in $X_{A,B}^L$ for some $C \in \Lambda_1^{A,B}$. Lemma 5.5.2 shows that X_C^L is locally closed in $X_{A,B}^L$, so X_C^L is open in $\overline{X_C^L} = X_{A,B}^L$. Irreducibility of $X_{A,B}^L$ shows that there is a unique open G_L -orbit, since two nonempty open sets in $X_{A,B}^L$ intersect nontrivially, thus any two open G_L orbits in $X_{A,B}^L$ coincide. \square

Let $A * B \in \Lambda_1$ be the matrix corresponding to the dense open G_L -orbit in $X_{A,B}^L$, so $\overline{X_{A*B}^L} = \overline{X_{A,B}^L}$.

5.7 Degenerations of orbits and the combinatorial partial order

Theorem 5.7.1. *Let $A, B \in \Lambda_1$ with $\text{ro}(A) = \text{ro}(B)$ and $\text{co}(A) = \text{co}(B)$, then $B \leq A$ if and only if $X_B^L \subset \overline{X_A^L}$ for any $L \in \mathcal{F}_{\text{ro}(A)}$.*

Proof. Let $\lambda = \text{co}(A)$, $\mu = \text{ro}(A)$ and fix $L \in \mathcal{F}_\mu$. Assume $N \in \mathbb{N}$ is chosen so that $X_A^L \subset \Pi_{N,\lambda}^a(L)$ and $X_B^L \subset \Pi_{N,\lambda}^b(L)$, where $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$. Then X_A^L is an open subset of the projective variety consisting of those $L' \in \Pi_{N,\lambda}^a(L)$ such that

$$\dim \left(\frac{L_i}{L_i \cap L'_j} \right) \leq d_{i,j}(A)$$

and

$$\dim \left(\frac{L'_j}{L_i \cap L'_j} \right) \leq \bar{d}_{i,j}(A),$$

for all $i, j \in \mathbb{Z}$.

Assume $X_B^L \subset \overline{X_A^L}$, then

$$d_{i,j}(B) = \dim \left(\frac{L_i}{L_i \cap L'_j} \right) \leq d_{i,j}(A)$$

and

$$\bar{d}_{i,j}(B) = \dim \left(\frac{L'_j}{L_i \cap L'_j} \right) \leq \bar{d}_{i,j}(A),$$

for each $i, j \in \mathbb{Z}$, for any $L' \in X_B^L$. So $B \leq A$ if $X_B^L \leq \overline{X_A^L}$.

Conversely, suppose $A \leq B$.

□

Corollary 5.7.2. *The maximum in $\Lambda_1^{A,B}$ is $A * B$.*

5.8 Associativity of the generic product

Let $A, B, C \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$ and $\text{co}(B) = \text{ro}(C)$ and fix $L \in \mathcal{F}_{\text{ro}(A)}$. Write $\lambda = \text{co}(A)$, $\mu = \text{co}(B)$ and $\nu = \text{co}(C)$. Define

$$Y_{A,B,C}^L = \left\{ (L', L'', L''') \in \mathcal{F}^3 : L' \in X_A^L, L'' \in X_B^L, L''' \in X_C^L \right\}$$

and

$$X_{A,B,C}^L = \left\{ L''' \in \mathcal{F} : \exists (L', L'') \in \mathcal{F}^2 \text{ with } (L', L'', L''') \in Y_{A,B,C}^L \right\}.$$

Lemma 5.8.1. *There is $N \in \mathbb{N}$ such that $Y_{A,B,C}^L$ is contained in $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}^{a+b+c}(L)$, where $a = d_{nN,0}(A)$, $b = d_{nN,0}(B)$ and $c = d_{nN,0}(C)$.*

Proof. Lemma 5.5.1 shows that there is $N \in \mathbb{N}$ such that $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0$, $\varepsilon^N L'_0 \subset L''_0 \subset \varepsilon^{-N} L'_0$ and $\varepsilon^N L''_0 \subset L'''_0 \subset \varepsilon^{-N} L''_0$ for each $(L', L'', L''') \in Y_{A,B,C}^L$. Using the proof of Lemma 5.6.1, it follows $L'' \in \Pi_{2N,\mu}^{a+b}(L)$ and $L''' \in \Pi_{2N,\nu}^{b+c}(L') \subset \Pi_{3N,\nu}^{a+b+c}(L)$. □

Assume $N \in \mathbb{N}$ is chosen so that $Y_{A,B,C}^L \subset \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}^{a+b+c}(L)$, where $a = d_{nN,0}(A)$, $b = d_{nN,0}(B)$ and $c = d_{nN,0}(C)$, as in Lemma 5.8.1.

Lemma 5.8.2. *$Y_{A,B,C}^L$ is a locally closed subset of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}^{a+b+c}(L)$. In particular, $Y_{A,B,C}^L$ is a quasiprojective variety.*

Proof. Write $\Pi = \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}(L)$. Then $Y_{A,B,C}^L$ consists of those $(L', L'', L''') \in \Pi$ satisfying the following conditions:

$$\dim \left(\frac{L_i}{L_i \cap L'_j} \right) = d_{i,j}(A), \quad (5.1)$$

$$\dim \left(\frac{L'_i}{L'_i \cap L''_j} \right) = d_{i,j}(B), \quad (5.2)$$

$$\dim \left(\frac{L''_i}{L''_i \cap L'''_j} \right) = d_{i,j}(C), \quad (5.3)$$

for $(i, j) \in [1, n] \times \mathbb{Z}$ with $i < j < (N+1)n$, and

$$\dim \left(\frac{L'_j}{L_i \cap L'_j} \right) = \bar{d}_{i,j}(A), \quad (5.4)$$

$$\dim \left(\frac{L''_j}{L'_i \cap L''_j} \right) = \bar{d}_{i,j}(B), \quad (5.5)$$

$$\dim \left(\frac{L'''_j}{L''_i \cap L'''_j} \right) = \bar{d}_{i,j}(C), \quad (5.6)$$

for $(i, j) \in [1, n] \times \mathbb{Z}$ with $-Nn < j < i$.

For $i < j$, the conditions

$$\begin{aligned} \dim(L_i/L_i \cap L'_j) &\leq d_{i,j}(A), \\ \dim(L'_i/L'_i \cap L''_j) &\leq d_{i,j}(B) \end{aligned}$$

and

$$\dim(L''_i/L''_i \cap L'''_j) \leq d_{i,j}(C)$$

define closed subsets of Π , by Lemma 5.4.7. For $i > j$, the conditions

$$\begin{aligned} \dim(L'_j/L_i \cap L'_j) &\leq \bar{d}_{i,j}(A), \\ \dim(L''_j/L'_i \cap L''_j) &\leq \bar{d}_{i,j}(B) \end{aligned}$$

and

$$\dim(L'''_j/L''_i \cap L'''_j) \leq \bar{d}_{i,j}(C)$$

also define closed subsets of Π .

On the other hand, the conditions $\dim(L_i/L_i \cap L'_j) \geq d_{i,j}(A)$, $\dim(L'_i/L'_i \cap L''_j) \geq d_{i,j}(B)$ and $\dim(L''_i/L''_i \cap L'''_j) \geq d_{i,j}(C)$ for $i < j$ define open subsets of Π . Similarly, the conditions $\dim(L'_j/L_i \cap L'_j) \geq \bar{d}_{i,j}(A)$, $\dim(L''_j/L'_i \cap L''_j) \geq \bar{d}_{i,j}(B)$ and $\dim(L'''_j/L''_i \cap L'''_j) \geq \bar{d}_{i,j}(C)$ for $i > j$ define open subsets of Π .

Therefore $Y_{A,B,C}^L$ is the intersection of finitely many closed sets in Π with finitely many open subsets of Π , so $Y_{A,B,C}^L$ is locally closed. In particular, $Y_{A,B,C}^L$ is a quasiprojective variety. \square

Lemma 5.8.3. For any $(L', L'', L''') \in Y_{A,B,C}^L$,

$$Y_{A,B,C}^L = \{ \alpha \cdot (L', \beta L'', \beta \gamma L''') : \alpha \in G_L, \beta \in G_{L'}, \gamma \in G_{L''} \}.$$

In particular,

$$Y_{A,B,C}^L = G_L \cdot (\{L'\} \times Y_{B,C}^{L'})$$

for each $L' \in X_A^L$.

Proof. Let $(L', L'', L''') \in Y_{A,B,C}^L$. Given $\alpha \in G_L$, $\beta \in G_{L'}$ and $\gamma \in G_{L''}$, $(\alpha L', \alpha \beta L'', \alpha \beta \gamma L''')$ is in $Y_{A,B,C}^L$ since

$$\begin{aligned} (L, \alpha L') &= \alpha(L, L') \in \mathcal{O}_A \\ (\alpha L', \alpha \beta L'') &= \alpha \beta(L', L'') \in \mathcal{O}_B \\ (\alpha \beta L'', \alpha \beta \gamma L''') &= \alpha \beta \gamma(L'', L''') \in \mathcal{O}_C \end{aligned}$$

For each $(N', N'', N''') \in Y_{A,B,C}^L$ there exist $\sigma_1, \sigma_2, \sigma_3 \in G$ with

$$\begin{aligned} (L, N') &= \sigma_1(L, L') \\ (N', N'') &= \sigma_2(L', L'') \\ (N'', N''') &= \sigma_3(L'', L'''). \end{aligned}$$

Let $\alpha = \sigma_1$, $\beta = \sigma_1^{-1} \sigma_2$ and $\gamma = \sigma_2^{-1} \sigma_3$, so $\sigma_2 = \alpha \beta$ and $\sigma_3 = \alpha \beta \gamma$. It follows that

$$(N', N'', N''') = (\alpha L', \alpha \beta L'', \alpha \beta \gamma L'''),$$

which proves the first claim. The second claim follows from the first since $(L'', L''') \in Y_{B,C}^{L'}$ and therefore

$$Y_{B,C}^{L'} = \{(\beta L'', \beta \gamma L''') : \beta \in G_{L'}, \gamma \in G_{L''}\},$$

as required. \square

Proposition 5.8.4. $Y_{A,B,C}^L$ is irreducible.

Proof. Write

$$\Pi = \Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}^{a+b+c}(L).$$

Lemma 5.4.2 shows that Π is a projective algebraic variety and Lemma 5.4.6 shows that $G_L/H_{3N,L}$ is a connected algebraic group acting algebraically on Π by the diagonal action.

Let $L' \in X_A^L$. As a result of Lemma 5.8.3

$$\begin{aligned} Y_{A,B,C}^L &= G_L \cdot (\{L'\} \times Y_{B,C}^{L'}) \\ &= G_L/H_{3N,L} \cdot (\{L'\} \times Y_{B,C}^{L'}). \end{aligned}$$

Proposition 5.6.4 shows that $Y_{B,C}^{L'}$ is irreducible, so $\{L'\} \times Y_{B,C}^{L'}$ is irreducible. The image of $\{L'\} \times Y_{B,C}^{L'}$ under the action of $G_L/H_{3N,L}$ is irreducible, since $G_L/H_{3N,L}$ is connected and therefore irreducible. Therefore $Y_{A,B,C}^L$ is irreducible. \square

Let p_3 be the projection of $\Pi_{N,\lambda}^a(L) \times \Pi_{2N,\mu}^{a+b}(L) \times \Pi_{3N,\nu}^{a+b+c}(L)$ onto the third factor. By the completeness property of projective varieties, p_3 is a closed morphism. The image of $Y_{A,B,C}^L$ under p_3 is $X_{A,B,C}^L$, so $p_3(\overline{Y_{A,B,C}^L}) = \overline{X_{A,B,C}^L}$.

Lemma 5.8.5. $X_{A,B,C}^L$ is irreducible and constructible.

Proof. Lemma 5.8.2 and Proposition 5.8.4 show that $Y_{A,B,C}^L$ is locally closed and irreducible. It follows $X_{A,B}^L$ is irreducible and constructible, since $X_{A,B,C}^L$ is the image of $Y_{A,B,C}^L$ under the morphism p_3 . \square

Lemma 5.8.6. There is a unique open and dense G_L -orbit in $X_{A,B,C}^L$.

Proof. There are only finitely many G_L -orbits in $X_{A,B,C}^L$. In particular,

$$X_{A,B,C}^L = \bigcup_{D \in \Lambda_1^{A,B}} X_{D,C}^L = \bigcup_{D \in \Lambda_1^{A,B}} \bigcup_{D' \in \Lambda_1^{D,C}} X_{D'}^L$$

and

$$\overline{X_{A,B,C}^L} = \bigcup_{D \in \Lambda_1^{A,B}} \bigcup_{D' \in \Lambda_1^{D,C}} \overline{X_{D'}^L}.$$

There is $D \in \Lambda_1$ such that $\overline{X_D^L} = \overline{X_{A,B,C}^L}$, since $X_{A,B,C}^L$ is irreducible, by Lemma 5.8.5. By Lemma 5.5.2, X_D^L is open in $\overline{X_D^L} = \overline{X_{A,B,C}^L}$, so X_D^L is open in $X_{A,B,C}^L$.

If X_D^L and $X_{D'}^L$ are open in $X_{A,B,C}^L$, then X_D^L and $X_{D'}^L$ have nonempty intersection since $X_{A,B,C}^L$ is irreducible, then $X_D^L = X_{D'}^L$. \square

Lemma 5.8.7. $p_3^{-1}(X_{A*B,C}^L)$ is open in $\overline{Y_{A,B,C}^L}$.

Proof. Projection onto the second component is a closed morphism of varieties $p_2: \overline{Y_{A,B,C}^L} \rightarrow \overline{X_{A,B}^L}$ with $p_2(Y_{A,B,C}^L) = X_{A,B}^L$. It follows that $p_3^{-1}(X_{A*B,C}^L)$ is open in $\overline{Y_{A,B,C}^L}$ since $p_3^{-1}(X_{A*B,C}^L) = p_2^{-1}(X_{A*B}^L)$ and X_{A*B}^L is open in $\overline{X_{A,B}^L}$. \square

Lemma 5.8.8. $p_3^{-1}(X_{A,B*C}^L)$ is open in $\overline{Y_{A,B,C}^L}$.

Proof. $p_3^{-1}(X_{A,B*C}^L)$ consists of those $(L', L'', L''') \in \overline{Y_{A,B,C}^L}$ such that $\dim(L'_i/L'_i \cap L_j''') \geq d_{i,j}(B * C)$ for $i < j$ and $\dim(L_j'''/L'_i \cap L_j''') \geq \bar{d}_{i,j}(B * C)$ for $i > j$. Each of these conditions defines an open subset of $\overline{Y_{A,B,C}^L}$ as a result of Lemma 5.4.7 and only finitely many conditions are required to determine $p_3^{-1}(X_{A,B*C}^L)$, as before. Therefore $p_3^{-1}(X_{A,B*C}^L)$ is the intersection of finitely many open sets in $\overline{Y_{A,B,C}^L}$, so is open as claimed. \square

Proposition 5.8.9. $X_{A*(B*C)}^L = X_{(A*B)*C}^L$.

Proof. The unique open G_L -orbit in $X_{A*B,C}^L$ is $X_{(A*B)*C}^L$, so $p_3^{-1}(X_{(A*B)*C}^L)$ is open in $p_3^{-1}(X_{A*B,C}^L)$. Lemma 5.8.7 shows that $p_3^{-1}(X_{A*B,C}^L)$ is open in $\overline{Y_{A,B,C}^L}$, so $p_3^{-1}(X_{(A*B)*C}^L)$ is open in $\overline{Y_{A,B,C}^L}$.

Similarly, $X_{A*(B*C)}^L$ is open in $X_{A,B*C}^L$, so $p_3^{-1}(X_{A*(B*C)}^L)$ is open in $p_3^{-1}(X_{A,B*C}^L)$. Lemma 5.8.8 shows that $p_3^{-1}(X_{A,B*C}^L)$ is open in $\overline{Y_{A,B,C}^L}$, so it follows $p_3^{-1}(X_{A*(B*C)}^L)$ is open in $\overline{Y_{A,B,C}^L}$.

Therefore $f^{-1}(X_{A*(B*C)}^L)$ has nonempty intersection with $f^{-1}(X_{(A*B)*C}^L)$, since $Y_{A,B,C}^L$ is irreducible by Proposition 5.8.4. It follows that the G_L -orbits $X_{A*(B*C)}^L$ and $X_{(A*B)*C}^L$ have nonempty intersection and therefore $X_{A*(B*C)}^L$ equals $X_{(A*B)*C}^L$. \square

5.9 The generic affine algebra

The generic affine algebra of rank r and period n , denoted by $\hat{G}(n, r)$, is a free \mathbb{Z} -module with basis $\{e_A : A \in \Lambda_1\}$ and \mathbb{Z} -bilinear multiplication given by

$$e_A * e_B = e_{A*B}$$

for $A, B \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$, and

$$e_A * e_B = 0$$

for $A, B \in \Lambda_1$ with $\text{co}(A) \neq \text{ro}(B)$.

Proposition 5.9.1. *The generic algebra $\hat{G}(n, r)$ is an associative \mathbb{Z} -algebra with 1, with*

$$1 = \sum_{\lambda \in \Lambda_0} 1_\lambda$$

where

$$1_\lambda = e_{D_\lambda},$$

for each $\lambda \in \Lambda_0$.

Proof. Let $A, B, C \in \Lambda_1$. If $\text{co}(A) \neq \text{ro}(B)$ or $\text{co}(B) \neq \text{ro}(C)$, then

$$(e_A * e_B) * e_C = 0 = e_A * (e_B * e_C),$$

so we may now suppose $\text{co}(A) = \text{ro}(B)$ and $\text{co}(B) = \text{ro}(C)$.

As a result of Proposition 5.8.9,

$$\begin{aligned} (e_A * e_B) * e_C &= e_{(A*B)*C} \\ &= e_{A*(B*C)} \\ &= e_A * (e_B * e_C), \end{aligned}$$

so it follows $\hat{G}(n, r)$ is an associative \mathbb{Z} -algebra.

The expression for the multiplicative identity follows from Lemma 3.1.7, since

$$e_A * \left(\sum_{\lambda \in \Lambda_0} 1_\lambda \right) = e_A * 1_{\text{co}(A)} = e_A$$

and

$$\left(\sum_{\lambda \in \Lambda_0} 1_\lambda \right) * e_A = 1_{\text{ro}(A)} * e_A = e_A,$$

for each $A \in \Lambda_1$. □

5.9.1 A categorical perspective

Proposition 5.9.2. *The following constitutes a small category: the set of objects is Λ_0 and the set of morphisms is Λ_1 . Given compositions $\lambda, \mu \in \Lambda_0$, the morphisms with source μ and target λ are those matrices $A \in \Lambda_1$ with $\text{co}(A) = \mu$ and $\text{ro}(A) = \lambda$. Given $\lambda, \mu, \nu \in \Lambda_0$ and $A, B \in \Lambda_1$ with $\text{co}(B) = \nu$, $\text{ro}(B) = \mu = \text{co}(A)$ and $\text{ro}(A) = \lambda$, their composition is $A * B$, with source $\text{co}(A * B) = \text{co}(B) = \nu$ and target $\text{ro}(A * B) = \text{ro}(A) = \lambda$.*

Proof. Proposition 5.8.9 shows that the generic product $*$ is associative. For each object $\lambda \in \Lambda_0$, the identity morphism $\lambda \rightarrow \lambda$ is the diagonal matrix D_λ . \square

Then the generic affine algebra $\hat{G}(n, r)$ may be realised as the \mathbb{Z} -algebra of this category. Observe that there are only finitely many objects in this category and distinct objects are non-isomorphic, so the isomorphism classes in this category are in one to one correspondence with Λ_0 . The \mathbb{Z} -algebra of this category is the free \mathbb{Z} -module on Λ_1 with \mathbb{Z} -bilinear multiplication given by the generic product $*$.

Chapter 6

A realisation of affine zero Schur algebras

The purpose of this chapter is to study the link between the generic affine algebra $\hat{G}(n, r)$ to the affine 0-Schur algebra $\hat{S}_0(n, r)$.

The main result is the construction of an isomorphism of \mathbb{Z} -algebras from $\hat{G}(n, r)$ to $\hat{S}_0(n, r)$ such that $E_i \mapsto E_i$, $F_j \mapsto F_j$ and $1_\lambda \mapsto 1_\lambda$, in the case that $n, r \geq 1$ with $r < n$.

6.1 Preliminary results on the generic affine algebra

Recall that the generic affine algebra $\hat{G}(n, r)$ is an associative \mathbb{Z} -algebra with a multiplicative basis $\{e_A : A \in \Lambda_1\}$ over \mathbb{Z} , where

$$e_A * e_B = e_{A*B}$$

for $A, B \in \Lambda_1$ with $\text{co}(A) = \text{ro}(B)$, and

$$e_A * e_B = 0$$

for $A, B \in \Lambda_1$ with $\text{co}(A) \neq \text{ro}(B)$.

6.1.1 Elementary basis elements

For $i \in \{1, \dots, n\}$ and $\lambda \in \Lambda_0$ such that $\lambda_{i+1} > 0$, define

$$E_{i,\lambda} = e_{D_\lambda + \mathcal{E}_{i,i+1} - \mathcal{E}_{i+1,i+1}}$$

and let

$$E_i = \sum_{\lambda \in \Lambda_0 : \lambda_{i+1} > 0} E_{i,\lambda}$$

for each $i \in \{1, \dots, n\}$

For $i \in \{1, \dots, n\}$ and $\lambda \in \Lambda_0$ such that $\lambda_i > 0$, define

$$F_{i,\lambda} = e_{D_\lambda + \mathcal{E}_{i+1,i} - \mathcal{E}_{i,i}}$$

and let

$$F_i = \sum_{\lambda \in \Lambda_0 : \lambda_i > 0} F_{i,\lambda}$$

for each $i \in \{1, \dots, n\}$.

Lemma 6.1.1. *Let $i \in \{1, \dots, n\}$ and $A \in \Lambda_1$ and write $\mu = \text{ro}(A)$.*

*If $\mu_{i+1} = 0$ then $E_i * e_A = 0$. If $\mu_{i+1} > 0$, then*

$$E_i * e_A = e_{A+\mathcal{E}_{i,p}-\mathcal{E}_{i+1,p}},$$

where

$$p = \max\{j \in \mathbb{Z} : a_{i+1,j} > 0\}.$$

If $\mu_i = 0$ then $F_i e_A = 0$. If $\mu_i > 0$ then

$$F_i * e_A = e_{A+\mathcal{E}_{i+1,q}-\mathcal{E}_{i,q}},$$

where

$$q = \min\{j \in \mathbb{Z} : a_{i,j} > 0\}.$$

Lemma 6.1.2. *Let $i \in \{1, \dots, n\}$ and $A \in \Lambda_1$ and write $\lambda = \text{co}(A)$.*

*If $\lambda_j = 0$ then $e_A * E_j = 0$. If $\lambda_j > 0$ then*

$$e_A * E_j = e_{A+\mathcal{E}_{p,j+1}-\mathcal{E}_{p,j}},$$

where

$$p = \min\{i \in \mathbb{Z} : a_{i,j} > 0\}.$$

*If $\lambda_{j+1} = 0$ then $e_A * F_j = 0$. If $\lambda_{j+1} > 0$ then*

$$e_A F_j = e_{A+\mathcal{E}_{q,j}-\mathcal{E}_{q,j+1}},$$

where

$$q = \max\{i \in \mathbb{Z} : a_{i,j+1} > 0\}.$$

6.1.2 Transpose involution

Let S be the \mathbb{Z} -module automorphism of $\hat{G}(n, r)$ given by

$$S e_A = e_{A^\top}$$

for each $A \in \Lambda_1$.

Lemma 6.1.3. *The map S is a \mathbb{Z} -algebra antihomomorphism. In particular,*

$$e_{A^\top} * e_{B^\top} = e_B * e_A,$$

for each $A, B \in \Lambda_1$.

Proof. Lemma 5.2.4 show that the transpose preserves the partial order on Λ_1 and so

$$(B * A)^\top = A^\top * B^\top,$$

using Lemma 4.1.1. □

Moreover,

$$\begin{aligned} S(E_{i,\lambda}) &= F_{i,\lambda+\alpha_i}, \\ S(F_{i,\lambda}) &= E_{i,\lambda-\alpha_i}, \text{ and} \\ S(1_\lambda) &= 1_\lambda. \end{aligned}$$

6.1.3 Shifting and periodicity

DEFINE THE ELEMENTS R AND R^{-1} , GIVE MULTIPLICATION RULES. What does the transpose do to R and R^{-1} .

6.2 Multiplicative bases in affine zero Schur algebras: motivating example

IN THIS SECTION IT WILL BE SHOWN THAT $\hat{S}_0(n, 1) = \hat{G}(n, 1)$.

In particular, there is an isomorphism of \mathbb{Z} -algebras $\hat{G}(2, 1) \rightarrow \hat{S}_0(2, 1)$ which sends e_A to e_A for each $A \in \Lambda_1$.

6.3 Presentation of the generic algebra.

Recall that Λ_0 denotes the set of compositions of r into n parts. That is, Λ_0 is the set of tuples $\lambda = (\lambda_1, \dots, \lambda_n) \in \mathbb{Z}^n$ with each λ_i non-negative and $\lambda_1 + \dots + \lambda_n = r$. Given $i \in [1, n]$, let $\varepsilon_i = (0, \dots, 1, \dots, 0) \in \mathbb{Z}^n$ be the i -th elementary vector and let $\alpha_i = \varepsilon_i - \varepsilon_{i+1}$. Then given $\lambda \in \Lambda_0$, we have $\lambda + \alpha_i \in \Lambda_0$ provided $\lambda_{i+1} > 0$ and $\lambda - \alpha_i \in \Lambda_0$ provided $\lambda_i > 0$.

Let $\Gamma = \Gamma(n, r)$ be the quiver with set of vertices Λ_0 with arrows $e_{i,\lambda}: \lambda \rightarrow \lambda + \alpha_i$ (if $\lambda_{i+1} > 0$) and $f_{i,\lambda}: \lambda \rightarrow \lambda - \alpha_i$ (if $\lambda_i > 0$). Thus there are no arrows between λ and μ unless $\lambda = \mu \pm \alpha_i$ for some $i \in [1, n]$.

If $n \geq 3$ then neighbouring vertices are connected by two arrows, one of each direction. In the case $n = 2$, neighbouring vertices are joined by four arrows, two of each direction. The $\mathbb{Z}\Gamma$ denote the path \mathbb{Z} algebra of Γ . By construction of Γ , there is a \mathbb{Z} -algebra homomorphism $\mathbb{Z}\Gamma \rightarrow \hat{G}(n, r)$ with $e_{i,\lambda} \mapsto E_{i,\lambda}$, $f_{i,\lambda} \mapsto F_{i,\lambda}$ and $k_\lambda = 1_\lambda$. We aim to describe the image and kernel of the morphism to give a presentation of the generic algebra by a quiver with relations, when possible. In general, we should obtain a presentation of a subalgebra of the generic algebra consisting of the so-called aperiodic elements (c.f. [32]).

Definition 6.3.1. (*aperiodicity*) $A \in \Lambda_1$ is aperiodic if for each $l \in \mathbb{Z} \setminus \{0\}$ there exists $i \in \mathbb{Z}$ such that $a_{i,i+l} = 0$. If $r < n$ then and $A \in \Lambda_1$ is aperiodic. Linear combinations of the basis elements corresponding to aperiodic matrices are also said to be aperiodic - if A is aperiodic, we say e_A is aperiodic.

Lemma 6.3.1. Let $A \in \Lambda_1$ and write $\lambda = \text{ro}(A)$. If A is aperiodic and $\lambda_{i+1} > 0$, then $E_i * e_A$ is aperiodic. If A is aperiodic and $\lambda_i > 0$, then $F_i * e_A$ is aperiodic.

Proof. Suppose $A \in \Lambda_1$ is aperiodic and $\lambda_{i+1} > 0$, where $\lambda = \text{ro}(A)$. There is $p \in \mathbb{Z}$ such that $a_{i+1,p} > 0$ and $a_{i+1,p'} = 0$ whenever $p' > p$. Lemma 6.1.1 shows that $E_i * e_A = e_B$, where $B = A + \mathcal{E}_{i,p} - \mathcal{E}_{i+1,p}$. Let $l \in \mathbb{Z} \setminus \{0\}$. If $l \notin \{p-i, p-i-1\}$, then $b_{s,s+l} = a_{s,s+l}$ for each $s \in \mathbb{Z}$, so there is $s \in \mathbb{Z}$ such that $b_{s,s+l} = a_{s,s+l} = 0$, since A is aperiodic. If $l = p-i$, then $b_{i+1,i+1+l} = b_{i+1,p+1} = a_{i+1,p+1} = 0$, by maximality of p . If $l = p-i-1$, there is $s \neq i+1$ such that $a_{s,s+l} = 0$, since A is aperiodic and $a_{i+1,i+1+l} = a_{i+1,p} > 0$, so $b_{s,s+l} = a_{s,s+l} = 0$. Therefore, $B = A + \mathcal{E}_{i,p} - \mathcal{E}_{i+1,p}$ is aperiodic.

Suppose $A \in \Lambda_1$ is aperiodic and $\lambda_i > 0$, where $\lambda = \text{ro}(A)$. Lemma 6.1.1 shows that $F_i * e_A = e_C$ where $C = A + \mathcal{E}_{i+1,p} - \mathcal{E}_{i,p}$ and $p = \min\{p' \in \mathbb{Z} : a_{i,p'} > 0\}$. Let $l \in \mathbb{Z} \setminus \{0\}$. If $l \notin \{p-i, p-i-1\}$ then $c_{s,s+l} = a_{s,s+l}$ for each $s \in \mathbb{Z}$, so there is $s \in \mathbb{Z}$ such that $c_{s,s+l} = a_{s,s+l} = 0$, by aperiodicity of A . If $l = p-i$, then $a_{i,i+l} = a_{i,p} > 0$, so there is $s \neq i$ such that $a_{s,s+l} = 0$. Then

$c_{s,s+l} = a_{s,s+l} = 0$. Finally, if $l = p - i - 1$, then $c_{i,i+l} = a_{i,p-1} = 0$ by minimality of p . Thus C is aperiodic as required. \square

Definition 6.3.2. (*Weight function*) Define the weight function $\text{wt}: \Lambda_1 \rightarrow \mathbb{Z}$ by

$$\text{wt } A = \sum_{i \in [1,n], j \in \mathbb{Z}} |j - i| a_{i,j}$$

for each $A \in \Lambda_1$. The sum is taken over a transversal of the set of congruence classes of (i, j) modulo (n, n) for $i, j \in \mathbb{Z}$.

Lemma 6.3.2. Let $A \in \Lambda_1$ and write $\lambda = \text{ro}(A)$. Suppose $\lambda_{i+1} > 0$ and set $p = \max\{p' \in \mathbb{Z} : a_{i+1,p'} > 0\}$. If $p > i$ then $\text{wt } e_{i,\lambda} * A = 1 + \text{wt } A$. If $p \leq i$ then $\text{wt } e_{i,\lambda} * A = -1 + \text{wt } A$. Suppose $\lambda_i > 0$ and set $q = \min\{q' \in \mathbb{Z} : a_{i,q'} > 0\}$. If $q \leq i$ then $\text{wt } f_{i,\lambda} * A = 1 + \text{wt } A$. If $q > i$ then $\text{wt } f_{i,\lambda} * A = -1 + \text{wt } A$.

Proof. Lemma 6.1.1 shows that $e_i A = A + \mathcal{E}_{i,p} - \mathcal{E}_{i+1,p}$, so $\text{wt } e_i A - \text{wt } A = |p - i| - |p - i - 1|$, which equals 1 if $p > i$ and equals -1 if $p \leq i$. Similarly, $f_i A = A + \mathcal{E}_{i+1,q} - \mathcal{E}_{i,q}$ by Lemma 6.1.1, so $\text{wt } f_i A - \text{wt } A = |q - i - 1| - |q - i|$, which equals -1 if $q > i$ and equals 1 if $q \leq i$. \square

Lemma 6.3.3. If $A \in \Lambda_1$ is aperiodic, then e_A may be obtained from $1_{\text{co}(A)}$ by finitely many applications of E_i and F_i for $i \in [1, n]$.

Proposition 6.3.4. The \mathbb{Z} -subalgebra of $\hat{G}(n, r)$ generated by $E_{i,\lambda}$, $F_{i,\lambda}$ and 1_λ has \mathbb{Z} -basis

$$\{e_A : A \in \Lambda_1 \text{ is aperiodic.}\}.$$

Proof. [COMPLETE THIS](#). \square

6.3.1 Relations

Suppose $n \geq 3$.

Lemma 6.3.5. The following relations hold in $\hat{G}(n, r)$:

$$E_i E_j - E_j E_i = 0$$

$$F_i F_j - F_j F_i = 0$$

unless $|j - i| = 1$.

$$E_i E_{i+1}^2 - E_{i+1} E_i E_{i+1} = 0$$

$$E_i^2 E_{i+1} - E_i E_{i+1} E_i = 0$$

$$F_{i+1} F_i^2 - F_i F_{i+1} F_i = 0$$

$$F_{i+1}^2 F_i - F_{i+1} F_i F_{i+1} = 0$$

$$E_i F_j - F_j E_i = 0$$

unless $j = i$.

$$E_i F_i - F_i E_i + \sum_{\lambda: \lambda_i=0, \lambda_{i+1}>0} 1_\lambda - \sum_{\lambda: \lambda_i>0, \lambda_{i+1}=0} 1_\lambda = 0.$$

6.3.2 The period 2 case

In this case, the quiver $\Gamma(2, r)$ has vertices $\Lambda_0[2, r] = \{(0, r), (1, r-1), \dots, (r, 0)\}$; adjacent vertices are connected by two pairs of arrows with opposite orientation: (e_1, f_1) and (e_2, f_2) . The relations arising from $\hat{G}(2, r)$ are of a more complicated form - in particular, the serre relations of total degree 3 will not hold in this case - so this case will be treated separately and at a later date.

Although, the presentation of the subalgebra of $\hat{G}(2, r)$ spanned by the aperiodic distinguished basis elements by a quiver with relations is not strictly needed for our study here, since we are considering the case where $r < n$, and we have already seen concretely why $\hat{G}(2, 1)$ and $\hat{S}_0(2, 1)$ are the same.

Chapter 7

Further directions

7.1 Further results on affine zero Schur algebras

[1] Investigate link between this generic product and the generic extension of representations. Shifting to the non-negative subalgebra to do computations purely in terms of generic extensions of quiver representations.

7.2 Deformed group algebras of symmetric groups

[2] Degenerate group algebras of symmetric groups: write down a presentation of the degenerate group algebras, with generators given by the transpositions, or 2-cycles. Type up the computations done for degenerate group algebras for S_3 and S_4 . Formulate propositions for the general case: the transpositions generate the degenerate group algebra; lemma: ‘these’ relations hold; these generators and relations give a presentation of the degenerate group algebras.

Terminology: deformed group algebra.

7.3 back matter

[1] $Y_{A,B}^L$ is the image of $G_L \times G_{L'}$ under the action map $(\alpha, \beta) \mapsto \alpha\beta \cdot (L', L'')$, for any $(L', L'') \in Y_{A,B}^L$. Lemma 5.4.6 shows that $G_L/H_{N,L}$ is a connected algebraic group. Moreover, $G_{L'}/H_{2N,L}$ is an irreducible affine variety, so $G_L/H_{N,L} \times G_{L'}/H_{2N,L}$ is an irreducible affine variety. It follows that $Y_{A,B}^L$ is irreducible and constructible.

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