

A geometric realisation of affine 0-Schur algebras.

Tom Crawley

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Chapter 1

Introduction

Chapter 2

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

2.1 Flag varieties as projective algebraic varieties

Include a discussion of flag varieties in a finite dimensional vector space. Explain: topology of projective space; Plücker embedding of Grassmannian in a projective space; flag varieties as a closed subset in a product of Grassmannians - show that the inclusion of one subspace into another is a closed condition - given by vanishing of some homogenous polynomials which should appear as minors of a matrix.

References for this material include [1][J. Harris: A First Course in Algebraic Geometry]; [2][D. Hudec: The Grassmannian as a Projective Variety]; [4][P. Morandi: Algebraic Groups, Grassmannians and Flag Varieties].

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 $i \in \mathbb{Z}$, given $g \in G$ 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: 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 on 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 [3, 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

Quivers with relations for 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,

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

□

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

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

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

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 $j = i$.

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

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 4.2.4 (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 $\rho^n = 1$.

4.3 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

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

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 Introducing the generic affine algebra

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. In particular, 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 $\mathrm{ro}, \mathrm{co}: \Lambda_1 \rightarrow \Lambda_0$ are the maps 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 a category with objects Λ_0 and morphisms Λ_1 ; where $\mathrm{Hom}(\lambda, \mu) = \{A \in \Lambda_1 : \mathrm{ro} A = \mu, \mathrm{co} A = \lambda\}$. Given $A, B \in \Lambda_1$ let $\Lambda_{1A,B}$ be the set of $C \in \Lambda_1$ such that there exist $L, L', L'' \in \mathcal{F}$ with $(L, L') \in \mathcal{O}_A$, $(L', L'') \in \mathcal{O}_B$ and $(L, L'') \in \mathcal{O}_C$. It will be shown that Λ_1 admits a partial order \leq such that, given $A, B \in \Lambda_1$ with $\mathrm{ro} B = \mathrm{co} A$, $\Lambda_{1A,B}$ has a maximum element $A * B$. It will be shown that $*$ is associative, leading to the construction of a category with the described properties.

The generic affine algebra $\hat{G}(n, r)$ is then defined to be the \mathbb{Z} -algebra of this category. It will be shown that $\hat{G}(n, r)$ gives a realisation of the affine 0-Schur algebra $\hat{S}_0(n, r)$ when $r < n$. It is expected that a more refined presentation of the generic algebra and the 0-Schur algebra will allow the conditions on the parameters to be relaxed slightly: the $r = n$ case is approachable, which may extend to the case $r < 2n$.

5.2 A partial order

Given $i, j \in \mathbb{Z}$, define a map $d_{i,j}$ on Λ_1 by setting

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

for each $A \in \Lambda_1$.

Lemma 5.2.1. *Let $A \in \Lambda_1$, with $A = (a_{i,j})_{i,j \in \mathbb{Z}}$ and write $d_{i,j} = d_{i,j}A$ for $i, j \in \mathbb{Z}$. Then*

$$d_{i,j} - d_{i-1,j} = \sum_{t > j} a_{i,t}$$

and

$$d_{i,j} - d_{i,j-1} = - \sum_{s \leq i} a_{s,j}.$$

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

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

Similarly,

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

□

Lemma 5.2.2. *Let $A \in \Lambda_1$, with $A = (a_{i,j})_{i,j \in \mathbb{Z}}$ and write $d_{i,j} = d_{i,j}A$ for each $i, j \in \mathbb{Z}$. Then*

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

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

Proof. Using Lemma 5.2.1,

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

Alternatively,

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

□

Lemma 5.2.3. *The relation \leq on Λ_1 , defined by $A \leq B$ if and only if $d_{i,j}A \leq d_{i,j}B$ for all $i, j \in \mathbb{Z}$, is a partial order.*

Proof. It is clear that \leq is reflexive and transitive, so it remains to see \leq is antisymmetric. 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 $i, j \in \mathbb{Z}$, which shows $A = B$ as a result of Lemma 5.2.2. \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 5.2.4. *Let $A \in \Lambda_1$ and take $(L, L') \in \mathcal{O}_A$. Then*

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

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

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

Conjecture 1. *Suppose $\mathbf{k} = \mathbb{C}$. The partial order on Λ_1 is compatible with the closure order on G -orbits in $\mathcal{F} \times \mathcal{F}$. In particular, $A \leq B$ if and only if $\mathcal{O}_A \subset \overline{\mathcal{O}_B}$.*

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 hold 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.

[CONFIRM THE VALIDITY OF THIS.] 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

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

with $\rho(L') = (L_1 / \varepsilon^N L_0, \dots, L_n / \varepsilon^N L_0)$.

Let \mathcal{F} be the space of $(U_1, \dots, U_n) \in \text{Gr}_{d_1}(W) \times \dots \times \text{Gr}_{d_n}(W)$ 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{F} is a closed subset of $\text{Gr}_{d_1}(W) \times \dots \times \text{Gr}_{d_n}(W)$, therefore \mathcal{F} is a projective algebraic variety.

The image of ρ is contained in \mathcal{F} 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 $(U_1, \dots, U_n) \in \mathcal{F}$. 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 $\text{im } \rho = \mathcal{F}$, 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 a subvariety of $\Pi_{N+1,\lambda}^{a+r}(L)$.*

Proof. If $L' \in \Pi_{N+1,\lambda}^{a+r}(L)$, 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 $L' \in \Pi_{N,\lambda}^a(L)$. Thus $\Pi_{N,\lambda}^a(L)$ is the subspace of $\Pi_{N+1,\lambda}^{a+r}(L)$ defined by the closed conditions $\varepsilon^N L_0 \subset L'_0$ and $L'_0 \subset \varepsilon^{-N} L_0$. □

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

Proof. $\Pi_{N,\lambda}^a(L)$ is naturally identified with the space of flags of subspaces

$$0 \subset U_1 \subset \cdots \subset U_n \subset \frac{\varepsilon^{-N-1}L_0}{\varepsilon^N L_0}$$

with $\dim(U_i/U_{i-1}) = \lambda_i$ for $i = 2, \dots, n$ and $\dim(W/U_n) = a$, satisfying the closed condition $\varepsilon U_n \subset U_1$. The image of $\Pi_{N,\lambda}^a(L) \cap \Pi_{\tilde{N},\lambda}^{\tilde{a}}(\tilde{L})$ under this identification is the subspace of flags (U_1, \dots, U_n) defined by the additional closed conditions $(\varepsilon^N L_0 + \varepsilon^{\tilde{N}} \tilde{L}_0)/\varepsilon^N L_0 \subset \varepsilon U_n$ and $U_n \subset (\varepsilon^{-N-1}L_0 \cap \varepsilon^{-\tilde{N}-1}\tilde{L}_0)/\varepsilon^N L_0$. Thus $\Pi_{N,\lambda}^a(L) \cap \Pi_{\tilde{N},\lambda}^{\tilde{a}}(\tilde{L})$ is a closed subset of $\Pi_{N,\lambda}^a(L)$ as claimed. \square

Remark 1. *The subsets $\Pi_{N,\lambda}^a(L)$ of \mathcal{F} are partially ordered by inclusion, the inclusions are closed and the set theoretic direct limit is the set \mathcal{F} , so \mathcal{F} may be endowed with the direct limit topology of a system of projective algebraic varieties.*

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

Given $N \in \mathbb{N}$, define

$$H_N = \left\{ h \in G_L : h = 1 \text{ on } \frac{\varepsilon^{-(1+N)}L_0}{\varepsilon^N L_0} \right\}.$$

Explicitly, the condition $h = 1$ on $\varepsilon^{-(1+N)}L_0/\varepsilon^N L_0$ means: $h(x) + \varepsilon^N L_0 = x + \varepsilon^N L_0$ for $x \in \varepsilon^{-(1+N)}L_0$. Observe that $H_{N+1} \subset H_N$ for $N \in \mathbb{N}$ since $h(x) + \varepsilon^N L_0 = x + \varepsilon^N L_0$ whenever $x \in \varepsilon^{-(1+N)}L_0$.

REDUNDANT:

Lemma 5.4.6. *H_N is a normal subgroup in G_L , for any $N \in \mathbb{N}$.*

Proof. H_N is the kernel of the group homomorphism $\bar{\cdot}: G_L \rightarrow \text{GL}(W)$. \square

EDITORIAL REMARK:

Maybe the cleanest way to write this is to describe the natural group homomorphism $G_L \rightarrow \text{GL}(W)$ and state that $H_{N,L}$ is the kernel of this group homomorphism. The next lemma should describe the image and deduce $G_L/H_{N,L}$ is a connected algebraic group, possibly with the last result relegated to a corollary.

Lemma 5.4.7. *Given $L \in \mathcal{F}$ and $N \in \mathbb{N}$, $G_L/H_{N,L}$ is a connected algebraic group.*

Proof. 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 . Given $g \in G_{L_0}$, g is a $\mathbb{C}[\varepsilon]$ -module automorphism of $\varepsilon^{-(1+N)}L_0$ and $\varepsilon^N L_0$ is a g -invariant submodule, so there is an automorphism $\bar{g}: W \rightarrow W$ fitting into a commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \varepsilon^N L_0 & \longrightarrow & \varepsilon^{-1-N} L_0 & \longrightarrow & W \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \varepsilon^N L_0 & \longrightarrow & \varepsilon^{-1-N} L_0 & \longrightarrow & W \longrightarrow 0 \end{array}$$

The natural map $\bar{\cdot}: G_{L_0} \rightarrow \mathrm{GL}(W)$ is a group homomorphism with kernel consisting of those $g \in G_{L_0}$ such that $\bar{g} = 1$: that is, $g(x) \in x + \varepsilon^{2N+1}L_0$ for each $x \in L_0$.

The image of G_{L_0} in $\mathrm{GL}(W)$ may be described by equations in the coordinates on $\mathrm{GL}(W)$ with respect to a \mathbb{C} -basis of W . W has a basis $\{x_1, \dots, x_r\}$ over $\mathbb{C}[\varepsilon]/\langle \varepsilon^{2N+1} \rangle$, therefore the complex vector space W has a basis $\{y_j : j \in \mathbb{Z}, 1 - 2Nr \leq j \leq r\}$ given by

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

for $1 \leq i \leq r$ and $0 \leq c \leq 2N$. There are coordinate functions $\gamma_{i,j}: \mathrm{GL}(W) \rightarrow \mathbb{C}$ with respect to this basis, given by

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

If $g \in \mathrm{GL}(W)$ is ε -linear, then $g(y_{i-r}) = g(\varepsilon y_i) = \varepsilon g(y_i)$ and therefore $\gamma_{i-r,j-r}(g) = \gamma_{i,j}(g)$ for all i, j . This shows that the image of G_{L_0} in $\mathrm{GL}(W)$ is the parabolic subgroup consisting of elements of the form

$$\begin{array}{c} A_0 A_1 A_2 \cdots A_{2N} \\ 0 A_0 A_1 \cdots A_{2N-1} \\ \dots\dots\dots \\ 0 \cdots 0 A_0 A_1 \\ 0 \cdots 0 A_0, \end{array}$$

where $A_0 \in \mathrm{GL}_r(\mathbb{C})$ and $A_1, \dots, A_{2N} \in M_r(\mathbb{C})$, which is a closed subgroup of $\mathrm{GL}(W)$. The image of G_{L_0} in $\mathrm{GL}(W)$ is identified with the (nonempty) open set $\mathrm{GL}_r(\mathbb{C}) \times M_r(\mathbb{C})^{2N}$ in the affine space $M_r(\mathbb{C})^{2N+1}$, so the image of G_{L_0} is irreducible. This shows that $G_{L_0}/H_{N,L_0}$ is a connected algebraic group.

Moreover, $G_L = G_{L_1} \cap \cdots \cap G_{L_n}$, so the image of G_L in $\mathrm{GL}(W)$ is a closed subgroup. $G_L/H_{N,L}$ is naturally isomorphic to the subgroup of $\mathrm{GL}(W)$ defined by the equations $\gamma_{i-r,j-r} = \gamma_{i,j}$ and for $j = 1, \dots, r$ the equations $\gamma_{i,j} = 0$ for $i > \lambda_1 + \cdots + \lambda_s$, where s is given by $\lambda_1 + \cdots + \lambda_{s-1} < j \leq \lambda_1 + \cdots + \lambda_s$. Therefore $G_L/H_{N,L}$ is isomorphic to the product $\mathcal{P}_\lambda \times M_r(\mathbb{C}) \times \cdots \times M_r(\mathbb{C})$, where \mathcal{P}_λ is a parabolic subgroup of $\mathrm{GL}(W)$, so is irreducible. \square

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 5.4.8. *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 projective variety.

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 a projective variety, so the intersection with $\Pi_{N,\lambda}^a(L) \times \Pi_{N,\mu}^b(L)$ is also a projective variety. \square

Lemma 5.4.9. *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 projective varieties.

Proof. This is a result of Lemma 5.3.2. \square

5.5 Geometry of orbits

Lemma 5.5.1. *Given $A \in \Lambda_1$, there is $N \in \mathbb{N}$ such that $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0$ for each $(L, L') \in \mathcal{O}_A$. In this case*

$$\dim \left(\frac{\varepsilon^{-N} L_0}{L'_0} \right) = d_{nN,0}(A).$$

Proof. Given $A \in \Lambda_1$, 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 5.2.4. \square

Lemma 5.5.2. *Given $A \in \Lambda_1$ and $L \in \mathcal{F}_{\text{ro } A}$, X_A^L is a quasiprojective variety. In particular, X_A^L is a locally closed subset of $\Pi_{N, \text{co } A}^a(L)$ for some $N \in \mathbb{N}$ and $a = d_{nN,0}(A)$.*

Proof. Lemma 5.5.1 shows that there is $N \in \mathbb{N}$ such that $X_A^L \subset \Pi_{N, \text{co } A}^a(L)$, where $a = d_{nN,0}(A)$. Then X_A^L is the subset of $\Pi_{N, \text{co } A}^a(L)$ given by the conditions $\dim(L_i/L_i \cap L'_j) = d_{i,j}(A)$ for $i, j \in \mathbb{Z}$. For each $i, j \in \mathbb{Z}$, the condition $\dim(L_i/L_i \cap L'_j)$ determines a locally closed subset of $\Pi_{N, \text{co } A}^a(L)$ since the function $L' \mapsto \dim(L_i/L_i \cap L'_j)$ is lower semicontinuous. Both $d_{i,j}(A)$ and $\dim(L_i/L_i \cap L'_j)$ are invariant under the map $(i, j) \mapsto (i+n, j+n)$, so X_A^L is determined by these conditions for $(i, j) \in [1, n] \times \mathbb{Z}$.

There are only finitely many $(i, j) \in [1, n] \times \mathbb{Z}$ such that $a_{i,j} > 0$ and

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

which shows that finitely many of these conditions determine X_A^L , so X_A^L is the intersection of finitely many locally-closed sets in $\Pi_{N, \text{co } A}^a(L)$ and is therefore locally closed. \square

Lemma 5.5.3. *Given $A \in \Lambda_1$ and $L \in \mathcal{F}_{\text{ro } A}$, X_A^L is an irreducible quasi-projective variety.*

Proof. Lemma 5.5.2 shows that X_A^L is a quasiprojective variety. In particular, X_A^L is a locally-closed subset of $\Pi_{N, \text{co } A}^a(L)$ for some $N \in \mathbb{N}$ and $a = d_{nN,0}(A)$. Lemma 5.4.7 shows $G_L/H_{N,L}$ is a connected algebraic group acting algebraically on $\Pi_{N, \text{co } A}^a(L)$, so each orbit is irreducible. In particular, if $L' \in X_A^L$, then $X_A^L = G_L \cdot L' = G_L/H_{N,L} \cdot L'$ is irreducible. \square

Consequently, the closure of X_A^L is an irreducible projective variety.

5.5.1 Geometry of orbit products

Suppose $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$. Recall the notation

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

and

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

$X_{A,B}$ is the image of $Y_{A,B}$ under the forgetful map $(L, L', L'') \mapsto (L, L'')$.

Lemma 5.5.4. *There is $N \in \mathbb{N}$ such that*

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

for each $(L, L'') \in X_{A,B}$.

Proof. There exist $N_1, N_2 \in \mathbb{N}$ such that

$$\varepsilon^{N_1} L_0 \subset L'_0 \subset \varepsilon^{-N_1} L_0$$

and

$$\varepsilon^{N_2} L'_0 \subset L''_0 \subset \varepsilon^{-N_2} L'_0,$$

for each $(L, L', L'') \in Y_{A,B}$. Then, for $(L, L', L'') \in Y_{A,B}$,

$$L''_0 \subset \varepsilon^{-N_2} L'_0 \subset \varepsilon^{-(N_1+N_2)} L_0$$

and

$$\varepsilon^{N_1+N_2} L_0 \subset \varepsilon^{N_2} L'_0 \subset L''_0.$$

In particular, taking $N = N_1 + N_2$, we have

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

for each $(L, L'') \in X_{A,B}$. □

Lemma 5.5.5. Suppose $N_1, N_2 \in \mathbb{N}$ with $\varepsilon^{N_1} L_0 \subset L_0 \subset \varepsilon^{-N_1} L_0$ and $\varepsilon^{N_2} L'_0 \subset L''_0 \subset \varepsilon^{-N_2} L'_0$ for each $(L, L', L'') \in Y_{A,B}$ and let $N = N_1 + N_2$. Then

$$\dim \left(\frac{\varepsilon^{-N} L_0}{L''_0} \right) = d_{nN_1,0}(A) + d_{nN_2,0}(B)$$

and

$$\dim \left(\frac{L''_0}{\varepsilon^N L_0} \right) = 2Nr - d_{nN_1,0}(A) + d_{nN_2,0}(B),$$

for each $(L, L'') \in X_{A,B}$.

Proof. Suppose $(L, L'') \in X_{A,B}$ and $L' \in \mathcal{F}$ so that $(L, L', L'') \in Y_{A,B}$. As in lemma 5.5.4, $\varepsilon^N L_0 \subset L''_0 \subset \varepsilon^{-N} L_0$, so

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

As a \mathbf{k} -vector space, $\varepsilon^{-N} L_0 / \varepsilon^N L_0$ is isomorphic to $(L_0 / \varepsilon L_0)^{2N}$, which has dimension $2Nr$, so

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

It remains to compute the codimension of L''_0 in $\varepsilon^{-N} L_0$. Note $L''_0 \subset \varepsilon^{-N_2} L'_0 \subset \varepsilon^{-N} L_0$, so

$$\dim \left(\frac{\varepsilon^{-N} L_0}{L''_0} \right) = \dim \left(\frac{\varepsilon^{-N} L_0}{\varepsilon^{-N_2} L'_0} \right) + \dim \left(\frac{\varepsilon^{-N_2} L'_0}{L''_0} \right).$$

$$\begin{aligned} \dim \left(\frac{\varepsilon^{-N} L_0}{\varepsilon^{-N_2} L'_0} \right) &= \dim \left(\frac{\varepsilon^{-N_1} L_0}{L'_0} \right) \\ &= \dim \left(\frac{L_{nN_1}}{L_{nN_1} \cap L'_0} \right) \\ &= \sum_{s \leq nN_1, t > 0} A_{s,t} \\ &= d_{nN_1,0}(A). \end{aligned}$$

$$\begin{aligned}
\dim \left(\frac{\varepsilon^{-N_2} L'_0}{L''_0} \right) &= \dim \left(\frac{L'_{nN_2}}{L'_{nN_2} \cap L''_0} \right) \\
&= \sum_{s \leq nN_2, t > 0} B_{s,t} \\
&= d_{nN_2,0}(B).
\end{aligned}$$

□

Refer to Section 3.1.1 for definitions of the spaces $X_{A,B}^L$ and $Y_{A,B}^L$.

Lemma 5.5.6. *Given $A, B \in \Lambda_1$ with $\text{ro } B = \text{co } A$ and $(L, L', L'') \in \mathcal{F}^3$ with $(L, L') \in \mathcal{O}_A$ and $(L', L'') \in \mathcal{O}_B$,*

$$\begin{aligned}
X_{A,B}^L &= G_L G_{L'} L'' \\
&= G_L X_B^{L'}.
\end{aligned}$$

Proof. $X_{A,B}^L$ is the image of $Y_{A,B}^L$ under the forgetful map $(N', N'') \mapsto N''$. If $\alpha \in G_L$ and $\beta \in G_{L'}$ then $(L, \alpha L, \alpha \beta L'') \in Y_{A,B}$ since $(L, \alpha L') = \alpha(L, L') \in \mathcal{O}_A$ and $(\alpha L', \alpha \beta L'') = \alpha \beta (\beta^{-1} L', L'') = \alpha \beta (L', L'') \in \mathcal{O}_B$. Consequently, $G_L G_{L'} L'' \in X_{A,B}^L$.

For the reverse inclusion, if $(N', N'') \in Y_{A,B}^L$ then $(L, N') \in \mathcal{O}_A$ and $(N', N'') \in \mathcal{O}_B$, so there exist $\sigma_1, \sigma_2 \in G$ such that $(L, N') = \sigma_1(L, L')$ and $(N', N'') \in \sigma_2(N', N'')$. Then $(L, N', N'') = (L, \sigma_1 L', \sigma_1 (\sigma_1^{-1} \sigma_2) L'')$ with $\sigma_1 \in G_L$ and $\sigma_1^{-1} \sigma_2 \in G_{L'}$. Thus $X_{A,B}^L = G_L G_{L'} L''$.

The second equality follows since $X_B^{L'} = G_{L'} L''$. □

Lemma 5.5.7. *There is $N \in \mathbb{N}$ such that $H_N \subset G_{L'}$. Consequently, $H_{N'} \subset G_{L'}$ whenever $N' \geq N$.*

Proof. Choose $N \in \mathbb{N}$ such that $\varepsilon^N L_0 \subset L'_0 \subset \varepsilon^{-N} L_0$. Then

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

Let $h \in H_N$. $h(x) + \varepsilon^N L_0 = x + \varepsilon^N L_0$ for $x \in \varepsilon^{-(1+N)} L_0$, so $h(L'_i) \subset L'_i$ for $i = 0, 1, \dots, n$. Moreover, h^{-1} stabilises L'_i , so $h(L'_i) = L'_i$ for $i = 0, 1, \dots, n$ and therefore for $i \in \mathbb{Z}$. This shows $h \in G_{L'}$ as required, so $H_N \subset G_{L'}$. □

H_N is generally not normal in $G_{L'}$, though the space of (right) cosets of H_N in $G_{L'}$ will still be irreducible.

Lemma 5.5.8. *$G_{L'}/H_N$ is irreducible, provided $H_N \subset G_{L'}$.*

Proof. Needs a proof. □

Lemma 5.5.9. *Given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $L \in \mathcal{F}_{\text{ro } A}$, $Y_{A,B}^L$ is a quasiprojective variety.*

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', L'') with $(L, L') \in \mathcal{O}_A$ and $(L', L'') \in \mathcal{O}_B$. Let $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$. Then $Y_{A,B}^L$ is the subset of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$ defined by the conditions

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

and

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

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

it remains to justify why these are locally closed conditions on the product and why there are effectively only finitely many conditions. Thus $Y_{A,B}^L$ is a locally closed subset of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$ so is a quasiprojective variety. \square

Proposition 5.5.10. *Given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $L \in \mathcal{F}_{\text{ro } A}$, $Y_{A,B}^L$ is an irreducible quasi-projective variety.*

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 $(L', L'') \in Y_{A,B}^L$. Write $a = d_{nN,0}(A)$ and $b = d_{nN,0}(B)$, so $Y_{A,B}^L \subset \Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$. Lemma 5.5.9 shows that $Y_{A,B}^L$ is a locally closed subset of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$ and thus a quasiprojective variety, so it remains to show $Y_{A,B}^L$ is irreducible.

For any $L' \in Y_{A,B}^L$, $Y_{A,B}^L = G_L \cdot (\{L'\} \times X_B^{L'}) = G_L/H_{2N,L} \cdot (\{L'\} \times X_B^{L'})$. $\overline{X_B^{L'}}$ is an irreducible subvariety of $\Pi_{N,\text{co } B}^b(L')$, which is a subvariety of $\Pi_{2N,\text{co } B}^{a+b}(L)$, so $\{L'\} \times \overline{X_B^{L'}}$ is an irreducible subvariety of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$. In particular, $\{L'\} \times X_B^{L'}$ is an irreducible (locally closed) subspace of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$. $G_L/H_{2N,L}$ is a connected algebraic group acting algebraically on $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L)$ and $Y_{A,B}^L$ is the image of $G_L/H_{2N,L} \times \{L'\} \times X_B^{L'}$ under the action map, so $Y_{A,B}^L$ is irreducible. \square

Lemma 5.5.11. *Given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $L \in \mathcal{F}_{\text{ro } A}$, $X_{A,B}^L$ is an irreducible topological space.*

Proof. $X_{A,B}^L$ is the image of $Y_{A,B}^L$ under the projection $\mathcal{F}_{\text{co } A} \times \mathcal{F}_{\text{co } B} \rightarrow \mathcal{F}_{\text{co } B}$ and $Y_{A,B}^L$ is irreducible, by Proposition 5.5.10, so $X_{A,B}^L$ is irreducible. \square

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 $(L, L') \in \mathcal{O}_A$ and $(L', L'') \in \mathcal{O}_B$. Then $\overline{X_B^{L'}}$ is an irreducible subvariety of $\Pi_{N,\text{co } B}^b(L')$, which is in turn a subvariety of $\Pi_{2N,\text{co } B}^{a+b}(L)$. Thus $X_B^{L'}$ is an irreducible subspace of $\Pi_{2N,\text{co } B}^{a+b}(L)$. $G_L/H_{2N,L}$ is a connected algebraic group acting morphically on $\Pi_{2N,\text{co } B}^{a+b}(L)$, therefore $X_{A,B}^L = G_L/H_{2N,L} \cdot X_B^{L'}$ is irreducible. \square

Remark 2. $X_{A,B}^L$ is a union of finitely many G_L -orbits, each of which is locally closed, so $X_{A,B}^L$ is constructible. Lemma 5.5.11 shows that $X_{A,B}^L$ is irreducible. Investigate whether $X_{A,B}^L$ is actually locally closed and therefore an irreducible quasiprojective variety.

Proposition 5.5.12. *Given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $L \in \mathcal{F}_{\text{ro } A}$, 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 5.5.11. Consequently, X_C^L is dense in $X_{A,B}^L$ for some $C \in \Lambda_{1A,B}$. 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 non-empty open sets in $X_{A,B}^L$ intersect non-trivially, thus any two open G_L orbits in $X_{A,B}^L$ coincide. \square

5.6 Existence of a maximum

Lemma 5.6.1. *Given $A, A' \in \Lambda_1$ with $\text{ro } A = \text{ro } A'$ and $\text{co } A = \text{co } A'$, $A' \leq A$ if and only if $X_{A'}^L \subset \overline{X_A^L}$ for any $L \in \mathcal{F}_{\text{ro } A}$.*

Proof. Needs a proof. \square

Proposition 5.6.2. *Given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$, $\Lambda_{1A,B}$ has a maximum element.*

Proof. Let $L \in \mathcal{F}_{\text{ro } A}$. $X_{A,B}^L$ is irreducible by Lemma 5.5.11 and is the union of finitely many G_L -orbits, namely

$$X_{A,B}^L = \bigcup_{C \in \Lambda_{1A,B}} X_C^L.$$

This shows that X_C^L is dense in $X_{A,B}^L$ for some $C \in \Lambda_{1A,B}$. Lemma 5.5.2 shows that the G_L -orbits in $X_{A,B}^L$ are locally closed, so a dense G_L -orbit is open in $X_{A,B}^L$. Lemma 5.6.1 shows that the characteristic matrix of the dense G_L -orbit is a maximum in $\Lambda_{1A,B}$. \square

5.7 Associativity

Refer to Section 3.1.2 for definitions of the spaces $X_{A,B,C}^L$ and $Y_{A,B,C}^L$. Recall that $X_{A,B,C}^L$ is the image of $Y_{A,B,C}^L$ under the forgetful map f , given by $f(L', L'', L''') = L'''$ for each $(L', L'', L''') \in Y_{A,B,C}^L$.

Lemma 5.7.1. *Given $A, B, C \in \Lambda_1$ with $\text{ro } C = \text{co } B$, $\text{ro } B = \text{co } A$ and a tuple of flags $(L, L', L'', L''') \in \mathcal{F}^4$ with $(L, L') \in \mathcal{O}_A$, $(L', L'') \in \mathcal{O}_B$ and $(L'', L''') \in \mathcal{O}_C$,*

$$X_{A,B,C}^L = G_L G_{L'} G_{L''} L'''.$$

Proof. Given $\alpha \in G_L$, $\beta \in G_{L'}$ and $\gamma \in G_{L''}$, $(L, \alpha L', \alpha \beta L'', \alpha \beta \gamma L''') \in Y_{A,B,C}^L$ since $(L, \alpha L') = \alpha(L, L') \in \mathcal{O}_A$, $(\alpha L', \alpha \beta L'') = \alpha \beta(L', L'') \in \mathcal{O}_B$ and $(\alpha \beta L'', \alpha \beta \gamma L''') = \alpha \beta \gamma(L'', L''') \in \mathcal{O}_C$. This shows $G_L G_{L'} G_{L''} L''' \in X_{A,B,C}^L$.

Given $(N', N'', N''') \in Y_{A,B,C}^L$, there exist $\sigma_1, \sigma_2, \sigma_3 \in G$ such that $(L, N') = \sigma_1(L, L')$, $(N', N'') = \sigma_2(L', L'')$ and $(N'', N''') = \sigma_3(L'', L''')$; then $N' = \sigma_1 L' = \sigma_2 L'$, $N'' = \sigma_2 L'' = \sigma_3 L''$ and $N''' = \sigma_3 L'''$. Thus

$$(L, N', N'', N''') = (L, \sigma_1 L', \sigma_1(\sigma_1^{-1} \sigma_2) L'', \sigma_1(\sigma_1^{-1} \sigma_2)(\sigma_2^{-1} \sigma_3) L''')$$

where $\sigma_1 \in G_L$, $\sigma_1^{-1} \sigma_2 \in G_{L'}$ and $\sigma_2^{-1} \sigma_3 \in G_{L''}$. \square

Lemma 5.7.2. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $Y_{A,B,C}^L$ is a quasiprojective variety.*

Proof. 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 $(L', L'', L''') \in Y_{A,B,C}^L$. Let $a = d_{nN,0}(A)$, $b = d_{nN,0}(B)$ and $c = d_{nN,0}(C)$. Then $Y_{A,B,C}^L$ is the subset of $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L) \times \Pi_{3N,\text{co } C}^{a+b+c}(L)$ defined by the conditions

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

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

and

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

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

it remains to show these conditions define locally closed subsets of the triple product and that there are effectively finitely many conditions.

Thus $Y_{A,B,C}^L$ is a locally closed subset of the projective variety $\Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L) \times \Pi_{3N,\text{co } C}^{a+b+c}(L)$, so $Y_{A,B,C}^L$ is a quasiprojective variety. \square

Lemma 5.7.3. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $Y_{A,B,C}^L$ is an irreducible quasiprojective variety.*

Proof. 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 $(L', L'', L''') \in Y_{A,B,C}^L$. Lemma 5.4.7 shows that $G_L/H_{3N,L}$ is a connected algebraic group acting algebraically on $\Pi = \Pi_{N,\text{co } A}^a(L) \times \Pi_{2N,\text{co } B}^{a+b}(L) \times \Pi_{3N,\text{co } C}^{a+b+c}(L)$.

Let $L' \in X_A^L$. $Y_{A,B,C}^L = G_L \cdot (\{L'\} \times Y_{B,C}^{L'})$. $Y_{B,C}^{L'}$ is an irreducible quasiprojective variety; $\overline{Y_{B,C}^{L'}}$ is an irreducible subvariety of $\Pi_{N,\text{co } B}^b(L') \times \Pi_{2N,\text{co } C}^{b+c}(L')$, which is a subvariety of $\Pi_{2N,\text{co } B}^{a+b}(L) \times \Pi_{3N,\text{co } C}^{a+b+c}(L)$. Thus $\{L'\} \times \overline{Y_{B,C}^{L'}}$ is an irreducible subvariety of Π . Therefore $Y_{A,B,C}^L$ is the image of the irreducible space $G_L/H_{3N,L} \times \{L'\} \times Y_{B,C}^{L'}$ under the action map, so $Y_{A,B,C}^L$ is irreducible. Lemma 5.7.2 shows that $Y_{A,B,C}^L$ is quasiprojective, so $Y_{A,B,C}^L$ is an irreducible quasiprojective variety. \square

Corollary 5.7.4. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $X_{A,B,C}^L$ is an irreducible topological space.*

Proof. $X_{A,B,C}^L$ is the image of $Y_{A,B,C}^L$ under the forgetful map f and $Y_{A,B,C}^L$ is irreducible, by Lemma 5.7.3, so $X_{A,B,C}^L$ is irreducible. \square

Lemma 5.7.5. *Given matrices $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, there is a unique open G_L -orbit in $X_{A,B,C}^L$.*

Proof. $X_{A,B,C}^L$ is irreducible, by Corollary 5.7.4, and consists of finitely many G_L -orbits, so contains a dense G_L -orbit. In particular, there is $D \in \Lambda_1$ such that $\overline{X_D^L} = X_{A,B,C}^L$. Lemma 5.5.2 shows that the G_L -orbits are locally closed in $X_{A,B,C}^L$. In particular, X_D^L is open in $\overline{X_D^L} = X_{A,B,C}^L$. Therefore, there is an open G_L -orbit in $X_{A,B,C}^L$. There is a unique open G_L -orbit since $X_{A,B,C}^L$ is irreducible. \square

Lemma 5.7.6. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $f^{-1}(X_{A*B,C}^L)$ is open in $Y_{A,B,C}^L$.*

Proof.

$$f^{-1}(X_{A*B,C}^L) = \left\{ (L', L'', L''') \in Y_{A,B,C}^L : \dim \left(\frac{L_i}{L_i \cap L_j''} \right) \text{ is maximal, for each } i, j \in \mathbb{Z} \right\}$$

is open in $Y_{A,B,C}^L$ since $f^{-1}(X_{A*B,C}^L)$ is defined by **finitely many** open conditions; the function on $X_{A,B}^L$ given by $L'' \mapsto \dim \left(\frac{L_i}{L_i \cap L_j''} \right)$ is lower semicontinuous, so maximising such a function is an open condition in $X_{A,B}^L$. \square

Lemma 5.7.7. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $f^{-1}(X_{A,B*C}^L)$ is open in $Y_{A,B,C}^L$.*

Proof.

$$f^{-1}(X_{A,B*C}^L) = \left\{ (L', L'', L''') \in Y_{A,B,C}^L : \dim \left(\frac{L'_i}{L'_i \cap L_j'''} \right) \text{ is maximal, for each } i, j \in \mathbb{Z} \right\}$$

is open in $Y_{A,B,C}^L$, as it is defined by **finitely many** open conditions; the function on $X_A^L \times X_{A,B*C}^L$ given by $(L', L''') \mapsto \dim \left(\frac{L'_i}{L'_i \cap L_j'''} \right)$ is lower semicontinuous, so maximising this function is an open condition on $X_A^L \times X_{A,B*C}^L$. \square

Conjecture 2. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and $L \in \mathcal{F}_{\text{ro } A}$, $X_{A*B,C}^L$ and $X_{A,B*C}^L$ are open and dense in $X_{A,B,C}^L$.*

Remark 3. *If f is shown to be an open map then this result follows from Lemma 5.7.6 and Lemma 5.7.7.*

Proposition 5.7.8. *Given $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$, $(A * B) * C = A * (B * C)$.*

Proof. Take $A, B, C \in \Lambda_1$ with $\text{co } A = \text{ro } B$ and $\text{co } B = \text{ro } C$ and fix $L \in \mathcal{F}_{\text{ro } A}$.

$X_{(A*B)*C}^L$ is open in $X_{A*B,C}^L$, so $f^{-1}X_{(A*B)*C}^L$ is open in $f^{-1}X_{A*B,C}^L$. Lemma 5.7.6 shows that $f^{-1}X_{A*B,C}^L$ is open in $Y_{A,B,C}^L$, so $f^{-1}X_{(A*B)*C}^L$ is open in $Y_{A,B,C}^L$. Similarly, $X_{A*(B*C)}^L$ is open in $X_{A,B*C}^L$ and $f^{-1}X_{A,B*C}^L$ is open in $Y_{A,B,C}^L$, by Lemma 5.7.7, so $f^{-1}X_{A*(B*C)}^L$ is open in $Y_{A,B,C}^L$.

Lemma 5.7.3 shows that $Y_{A,B,C}^L$ is irreducible, so $f^{-1}X_{(A*B)*C}^L$ and $f^{-1}X_{A*(B*C)}^L$ have nonempty intersection. Therefore the G_L -orbits $X_{(A*B)*C}^L$ and $X_{A*(B*C)}^L$ intersect nontrivially, so are the same G_L -orbit. In particular, $(A * B) * C = A * (B * C)$. \square

5.8 The generic algebra

Lemma 5.8.1. *Given $\lambda \in \Lambda_0$ and $A \in \Lambda_1$, $D_\lambda * A = A$ if $\text{ro } A = \lambda$ and $A * D_\lambda = A$ if $\text{co } A = \lambda$.*

Proof. Lemma 3.1.7 shows that $\Lambda_{1D_\lambda,A} = \{A\}$ if $\lambda = \text{ro } A$ and $\Lambda_{1A,D_\lambda} = \{A\}$ if $\lambda = \text{co } A$, which proves the result. \square

Theorem 5.8.2. *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 λ and target μ are those matrices $A \in \Lambda_1$ with $\text{co } A = \lambda$ and $\text{ro } A = \mu$. Given $\lambda, \mu, \nu \in \Lambda_0$ and $A, B \in \Lambda_1$ with $B: \lambda \rightarrow \mu$ and $A: \mu \rightarrow \nu$ the composition is $A * B: \lambda \rightarrow \nu$.*

Proof. Proposition 5.6.2 shows that the composition is well defined while Proposition 5.7.8 establishes associativity of the composition. Lemma 5.8.1 shows that $D_\lambda: \lambda \rightarrow \lambda$ is the identity morphism for each $\lambda \in \Lambda_0$. Thus $(\Lambda_0, \Lambda_1, \text{co}, \text{ro}, *)$ is a category. \square

Write $\mathcal{G}(n, r)$ to denote this so-called ‘generic category’.

Example 1. *The objects in $\mathcal{G}(2, 2)$ are compositions of 2 into 2 parts, namely $(0, 2)$, $(1, 1)$ and $(2, 0)$. The set of morphisms from λ to μ is the set of infinite periodic matrices $A \in \Lambda_1[2, 2]$ with $\text{co } A = \lambda$ and $\text{ro } A = \mu$, which is a countably infinite set for any pair of compositions $\lambda, \mu \in \Lambda_0[2, 2]$.*

Definition 5.8.1 (Generic algebra). *The generic affine algebra $\hat{G}(n, r)$ is the category \mathbb{Z} -algebra of $\mathcal{G}(n, r)$. In particular, $\hat{G}(n, r)$ is a free \mathbb{Z} -module with basis $\{e_A : A \in \Lambda_1\}$ and with associative multiplication given by*

$$e_A * e_B = \begin{cases} e_{A*B} & \text{if } \text{co } A = \text{ro } B \\ 0 & \text{if } \text{co } A \neq \text{ro } B. \end{cases}$$

The multiplicative identity in $\hat{G}(n, r)$ is

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

Chapter 6

A realisation of affine zero Schur algebras

We aim to prove the isomorphism theorem in the cases $r < n$ and $n \leq r < 2n$ separately. Below are crude versions of the statements we want to prove.

Theorem 6.0.1. *Assume $r < n$. The map $\psi: \hat{G}(n, r) \rightarrow \hat{S}_0(n, r)$, given by $\psi(E_i) = E_i$, $\psi(F_i) = F_i$ and $\psi(1_\lambda) = 1_\lambda$, is an isomorphism of \mathbb{Z} -algebras.*

Theorem 6.0.2. *Assume $n \leq r < 2n$. There is a unique homomorphism of \mathbb{Z} -algebras $\hat{\psi}: \hat{G}(n, r) \rightarrow \hat{S}_0(n, r)$ such that $\hat{\psi}(R) = R$ and $\hat{\psi} = \psi$ on the subalgebra of $\hat{G}(n, r)$ generated by the E_i , F_i and 1_λ . $\hat{\psi}$ is an isomorphism of \mathbb{Z} -algebras.*

6.1 Preliminary results

Recall from Definition 5.8.1 that the generic algebra $\hat{G}(n, r)$ is an associative \mathbb{Z} -algebra which is a free \mathbb{Z} -module with an atomic basis $\{e_A : A \in \Lambda_1\}$: given $A, B \in \Lambda_1$ with $\text{co } A = \text{ro } B$, $e_A e_B = e_{A*B}$.

6.1.1 Elementary basis elements

Given $i \in [1, n]$ 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

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

Given $i \in [1, n]$ 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

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

6.1.2 Transpose involution

Lemma 6.1.1. *The \mathbb{Z} -module automorphism \top of $\hat{G}(n, r)$ given by $e_A \mapsto e_{A^\top}$ is a \mathbb{Z} -algebra antihomomorphism: that is,*

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

for each $A, B \in \Lambda_1$. Moreover, $\top(E_{i,\lambda}) = F_{i,\lambda+\alpha_i}$, $\top(F_{i,\lambda}) = E_{i,\lambda-\alpha_i}$ and $\top(1_\lambda) = 1_\lambda$, for permissible $(i, \lambda) \in \mathbb{Z} \times \Lambda_0$.

Proof. This is a consequence of Lemma 4.1.1. [It must also be shown that the transpose operation on \$\Lambda_1\$ is order preserving.](#) \square

6.1.3 Multiplication rules

Lemma 6.1.2. *Given $A \in \Lambda_1$ and $i \in [1, n]$ such that $\text{ro } A_{i+1} > 0$,*

$$E_i e_A = e_{A+\varepsilon_{i,p}-\varepsilon_{i+1,p}},$$

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

Given $A \in \Lambda_1$ and $i \in [1, n]$ such that $\text{ro } A_i > 0$,

$$F_i e_A = e_{A+\varepsilon_{i+1,p}-\varepsilon_{i,p}},$$

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

Similar formulas for right multiplication by E_i and F_i are obtained by applying the transpose.

6.2 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. [3]).

Definition 6.2.1. *(aperiodicity) $A \in \Lambda_1$ is aperiodic if for each $l \in \mathbb{Z} \setminus \{0\}$ there exists $i \in \mathbb{Z}$ such that $a_{i,i+l} = 0$. Denote the set of aperiodic elements in Λ_1 by Λ_1^{ap} . Note that $\Lambda_1^{\text{ap}} = \Lambda_1$ if $r < n$. 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 6.2.1. *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 6.1.2 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 6.1.2 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 6.2.2. (*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 6.2.2. 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 6.1.2 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 6.1.2, 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 6.2.3. 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 6.2.4. The \mathbb{Z} -subalgebra of $\hat{G}(n, r)$ generated by $E_{i,\lambda}$, $F_{i,\lambda}$ and 1_λ has \mathbb{Z} -basis $\{e_A : A \in \Lambda_1^{\text{ap}}\}$, where $\Lambda_1^{\text{ap}} \subset \Lambda_1$ is the set of aperiodic elements.

Proof. \square

6.2.1 The typical case.

Lemma 6.2.5. The following relations hold in $\hat{G}(n, r)$ ($n \geq 3$):

$$E_i E_j - E_j E_i = 0$$

$$F_i F_j - F_j F_i = 0$$

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 $j = i$.

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

6.2.2 Exceptional 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.

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.

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