

# 1 Introduction

We will review the definition of a Springer fiber and define, for a nilpotent  $Y \in \mathfrak{gl}_m$ , the Springer fiber at the  $n$ -Slodowy slice at  $Y$ . For every  $n$  and every nilpotent  $Y \in \mathfrak{gl}_m$ , we will find the irreducible components of the Springer fiber at the  $n$ -Slodowy slice at  $Y$ . Finally, we will use our results about Springer fibers at  $n$ -Slodowy slices to find the irreducible components of some other variety (which probably needs a name), and show that they all have the same dimension.

## 2 Preliminary Definitions and Facts

### 2.1 Conventions and Notations

We write  $GL_m, \mathfrak{sl}_m$  to denote  $GL_m(\mathbb{C}), \mathfrak{sl}_m(\mathbb{C})$ , and so on. By  $J_m$  we refer to the nilpotent  $m \times m$  Jordan block (which, by convention, has ones *below* the diagonal). Given a partition  $\lambda = (\lambda_1, \dots, \lambda_k)$ , we write  $J(\lambda)$  to denote the block matrix

$$\begin{pmatrix} J_{\lambda_1} & & \\ & \ddots & \\ & & J_{\lambda_k} \end{pmatrix}.$$

### 2.2 Springer fibers

Let  $\mathfrak{g}$  be a Lie algebra. Let  $\mathcal{N} \subseteq \mathfrak{g}$  be the subset consisting of nilpotent elements. Let  $\mathcal{B}$  be the variety of Borel subalgebras of  $\mathfrak{g}$ . Let  $\tilde{\mathcal{N}} = \{(\mathfrak{b}, n) : n \in \mathfrak{b}\} \subseteq \mathcal{B} \times \mathcal{N}$ . Let  $\pi : \tilde{\mathcal{N}} \rightarrow \mathcal{N}$  be the projection onto the second coordinate. We call this the *Springer resolution*. For  $n \in \mathcal{N}$ , we call  $\pi^{-1}(n)$  the *Springer fiber at  $n$* .

### 2.3 Springer fibers in $\mathfrak{gl}_m$

Now we let  $\mathcal{N}_m$  be the set of nilpotent elements in  $\mathfrak{gl}_m$ , and  $\mathcal{B}_m$  the variety of Borel subalgebras of  $\mathfrak{gl}_m$ . Let  $H \subseteq \mathfrak{gl}_m$  be the subalgebra of upper triangular matrices. The variety of Borel subalgebras of  $\mathfrak{gl}_m$  is  $\mathcal{B} = \{gHg^{-1} : g \in GL_m\}$ . Thus, the Springer fiber at  $X \in \mathcal{N}$  is

$$S_X = \{gHg^{-1} : X \in gHg^{-1}\}.$$

**Definition 2.1.** A flag  $(V_i)$  of  $\mathbb{C}^m$  is a sequence of subspaces

$$0 = V_0 \subseteq V_1 \subseteq \cdots \subseteq V_m = \mathbb{C}^m,$$

where  $\dim V_i = i$ .

We say that  $X \in \mathfrak{gl}_m$  preserves a flag  $(V_i)$  if  $\forall i. XV_i \subseteq V_i$ . Note that  $X \in \mathcal{N}$  preserves a flag  $(V_i)$  if and only if  $\forall i. XV_i \subseteq V_{i-1}$ .

The simplest flag is the *standard flag*  $(E_i)$ , where  $E_i := \langle e_1, \dots, e_i \rangle$ . Note that the group  $H$  is exactly the subset of  $\mathfrak{gl}_m$  which preserves  $E_i$ .

We can think of  $\mathcal{B}$  as the set of flags of  $\mathbb{C}^m$ , via the correspondence

$$gHg^{-1} \leftrightarrow (gE_i).$$

Note that  $X$  preserves  $(gE_i)$  if and only if  $X \in gHg^{-1}$ . Thus, we may write the Springer fiber at  $X \in \mathcal{N}$  in terms of flags, as

$$S_X = \{(gE_i) : X \in gHg^{-1}\} = \{(V_i) : \forall i. XV_i \subseteq V_{i-1}\}.$$

**Theorem 2.2.** (Needs citation!) *The irreducible components of the Springer fiber at  $J(\mu)$  are in bijection with the standard Young tableaux of shape  $\mu$ . Further, the irreducible components are equidimensional, of dimension  $\sum_{i \neq j} \min(\mu_i, \mu_j) = \sum_i (i-1)\mu_i$ .*

## 2.4 Slodowy Slices

A basis for  $\mathfrak{sl}_2$  is

$$e' := \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, h' := \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, f' := \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}.$$

Given a Lie algebra  $\mathfrak{g}$ , and a homomorphism  $\phi : \mathfrak{sl}_2 \rightarrow \mathfrak{g}$  sending  $(e', h', f')$  to  $(e, h, f)$ , we say that  $(e, h, f)$  is an  $\mathfrak{sl}_2$ -triple. Observe that  $e, f$  must be nilpotent, and  $h$  must be Cartan (TODO: what?) If  $\mathfrak{g}$  is semisimple, then given any nilpotent  $e \in \mathfrak{g}$ , the Jacobson-Morozov theorem [1, 3.7.1] says that there exist  $h, f \in \mathfrak{g}$  such that  $(e, h, f)$  is an  $\mathfrak{sl}_2$ -triple.

Given  $(e, h, f)$ , we define the *Slodowy slice at  $e$*  as  $\mathcal{S}_e := e + \ker \text{ad}_f$ . By the Jacobson-Morozov theorem, we can always find a Slodowy slice at any nilpotent  $e \in \mathfrak{g}$ , when  $\mathfrak{g}$  is semisimple.

### 3 Linear Algebra Facts

In this section we prove linear algebra facts that will be useful later. A reader uninterested in their verification may wish to read the theorem statements and skip ahead to the next section.

#### 3.1 The centralizer of a nilpotent matrix

**Definition 3.1.** A matrix  $Y$  is Toeplitz if it is constant along bands parallel to the main diagonal. That is,  $\forall i, j, k. Y_{ij} = Y_{i+k, j+k}$ .

**Definition 3.2.** An  $m \times n$  matrix  $Y$  is lower-left Toeplitz if it is Toeplitz and, in addition, we have  $y_{n-i, j-1} = 0$  whenever  $i + j \geq \min(m, n)$ .

That is,  $Y$  is lower-left Toeplitz if it is Toeplitz, and the only nonzero entries are those with Manhattan distance less than  $\min(m, n)$  from the entry in the bottom-left corner. In yet other words, all but the leftmost (equivalently, bottommost)  $\min(m, n)$  diagonal bands are zero.

**Lemma 3.3.** Let  $\lambda = (\lambda_1, \dots, \lambda_k)$  be a partition of  $m$ . The centralizer of  $J(\lambda)$  in  $\mathfrak{gl}_m$  is the subalgebra consisting of matrices

$$M = \begin{pmatrix} M_{11} & \cdots & M_{1k} \\ \vdots & & \vdots \\ M_{k1} & \cdots & M_{kk} \end{pmatrix},$$

where each  $M_{ij}$  is a  $\lambda_i \times \lambda_j$  matrix, such that each  $M_{ij}$  is lower-left Toeplitz.

*Proof.* Let

$$M = \begin{pmatrix} M_{11} & \cdots & M_{1k} \\ \vdots & & \vdots \\ M_{k1} & \cdots & M_{kk} \end{pmatrix}.$$

We need to show that  $J(\lambda)M = MJ(\lambda)$  if and only if each  $M_{ij}$  is lower-left Toeplitz.

We have

$$J(\lambda)M = \begin{pmatrix} J_{\lambda_1}M_{11} & \cdots & J_{\lambda_1}M_{1k} \\ \vdots & & \vdots \\ J_{\lambda_k}M_{k1} & \cdots & J_{\lambda_k}M_{kk} \end{pmatrix}, \text{ and } MJ(\lambda) = \begin{pmatrix} M_{11}J_{\lambda_1} & \cdots & M_{1k}J_{\lambda_k} \\ \vdots & & \vdots \\ M_{k1}J_{\lambda_1} & \cdots & M_{kk}J_{\lambda_k} \end{pmatrix}.$$

So, we have  $J(\lambda)M = MJ(\lambda)$  if and only if  $\forall i, j. J_{\lambda_i}M_{ij} = M_{ij}J_{\lambda_j}$ . Multiplying on the left by  $J_{\lambda_i}$  just shifts each row down by one, and multiplying on the right by  $J_{\lambda_j}$  shifts each column left by one. The matrices for which left-shifting gives the same result as down-shifting are exactly the lower-left Toeplitz matrices.  $\square$

For nilpotent  $X$  in Jordan form and  $a$  in ‘normalized’ form (i.e., with at most one nonzero element, which is a one), we will find the centralizer of  $A_{X,a,b}$  in

$$\{(A, I) : A \in \mathfrak{gl}_m\} \subseteq \mathfrak{gl}_{m+n}.$$

Note that an element of the form  $(A, I)$  commutes with  $A_{X,a,b}$  if and only if  $A$  commutes with  $X$ , and  $aA = a$ , and  $Ab = b$ . So, we just have to find

$$\{A \in \mathfrak{gl}_m : AX = XA, aA = a, Ab = b\}.$$

It is just the set of  $A = [A_{ij}]_{ij}$ , where each  $A_{ij}$  is lower-left-Toeplitz.

Let  $v_{ij}$  be the leftmost column of  $A_{ij}$ , so that

$$A_{ij} = \begin{pmatrix} v_{ij} \bowtie 0 & \cdots & v_{ij} \bowtie [\lambda_j - 1] \end{pmatrix}.$$

Since  $A_{ij}$  is lower-left-Toeplitz,  $v_{ij}$  is of the form

$$v_{ij} = \begin{pmatrix} 0 \\ v'_{ij} \end{pmatrix},$$

where  $v'_{ij} \in \mathbb{C}^{\min(\lambda_i, \lambda_j)}$  can be chosen freely. Now we determine which matrices of this form satisfy  $aA = a$ . For simplicity, we will instead find the matrices  $A$  such that  $aA = 0$  (so that  $a(A + I) = a$ ). (Note that  $I \in C_1$ , and  $C_1$  is closed under addition, so this is really the same thing.)

In the case that  $a = 0$ , clearly every  $A$  works. Otherwise, let  $i_0, j_0$  be such that  $a_{i_0, j_0} = 1$ . Now, clearly the constraint that  $aA = 0$  is just saying that the  $(i_0, j_0)$ th row of  $A$  must be zero. That is, for each  $j$  the  $j_0$ th row of  $A_{i_0 j}$  must be zero. This just requires that for each  $j$ , we must have

$$v_{ij} = \begin{pmatrix} 0 \\ v'_{ij} \end{pmatrix},$$

where  $v'_{ij} \in \mathbb{C}^{\min(\lambda_i - j_0, \lambda_j)}$  can be chosen freely. So, we have now found the set

$$C_2 := \{A \in \mathfrak{gl}_m : AX = XA, aA = a\}.$$

It is the matrices of the form  $I + A$ , where  $A_{ij}$  is a block matrix of size  $\lambda_i \times \lambda_j$  with

$$A_{ij} = T(v_{ij}) = T \begin{pmatrix} 0 \\ v'_{ij} \end{pmatrix},$$

where  $v'_{ij} \in \mathbb{C}^{\min(\lambda_i, \lambda_j)}$  in the case  $i \neq i_0$  and  $v'_{ij} \in \mathbb{C}^{\min(\lambda_i - j_0, \lambda_j)}$  if  $i = i_0$ .

### 3.2 A ‘normalization’ fact about Jordan bases

**Lemma 3.4.** *For any finite-dimensional  $V$ , nilpotent  $A : V \rightarrow V$ , and linear  $f : V \rightarrow \mathbb{C}$ , there is a Jordan basis  $e_{ij}$  for  $A$  such that there is at most one  $i$  such that there exists  $j$  such that  $f(e_{ij}) \neq 0$ .*

*Proof.* For any Jordan basis  $(e_{ij})_{ij}$  of  $A$ , define

$$S((e_{ij})_{1 \leq i \leq k, 1 \leq j \leq \lambda_i}) := \sum_i \begin{cases} -1, & \forall j. f(e_{ij}) = 0 \\ \lambda_i - \min\{j : f(e_{ij}) \neq 0\}, & \text{otherwise} \end{cases}.$$

We proceed by induction on the measure  $S$ . That is, let  $(e_{ij})_{ij}$  be a Jordan basis for  $A$ . Our inductive hypothesis is that if there exists a Jordan basis  $(e'_{ij})_{ij}$  with  $S((e'_{ij})_{ij}) < S((e_{ij})_{ij})$ , then we get the desired conclusion.

Now, we have two cases. In the first case,  $(e_{ij})_{ij}$  already satisfies the desired property. In this case we are done. In the other case, there exist  $i_1, j_1, i_2, j_2$  with  $i_1 \neq i_2$ , and  $f(e_{i_1 j_1}) \neq 0$ , and  $f(e_{i_2 j_2}) \neq 0$ . We let  $j_1, j_2$  be minimal with this property, so that  $\forall j < j_1. f(e_{i_1 j}) = 0$ , and  $\forall j < j_2. f(e_{i_2 j}) = 0$ . Wlog, we assume that  $\lambda_{i_1} - j_1 \leq \lambda_{i_2} - j_2$ .

By our inductive hypothesis, all we need to do is find a Jordan basis  $(e'_{ij})_{ij}$  with  $S((e'_{ij})_{ij}) < S((e_{ij})_{ij})$ . This is what we do. Define  $e'_{ij}$  as follows.

- $e'_{i_1, \lambda_1} := e_{i_1, \lambda_1} - \frac{f(e_{i_1, j_1})}{f(e_{i_2, j_2})} e_{i_2, j_2 + (\lambda_{i_1} - j_1)}$
- For  $j < \lambda_1$ ,  $e'_{i_1, j} := A^{\lambda_{i_1} - j} e'_{i_1, \lambda_1}$
- For  $i \neq i_1$ ,  $e'_{ij} := e_{ij}$ .

Clearly this is a Jordan basis for  $A$ . Further, I claim that  $S((e'_{ij})_{ij}) < S((e_{ij})_{ij})$ . It suffices to show that  $\forall j \leq j_1. f(e_{i_1, j}) = 0$ . We have

$$f(e'_{i_1, j}) = f \left( A^{\lambda_{i_1} - j} \left( e_{i_1, \lambda_1} - \frac{f(e_{i_1, j_1})}{f(e_{i_2, j_2})} e_{i_2, j_2 + (\lambda_{i_1} - j_1)} \right) \right) =$$

$$f\left(e_{i_1,j} - \frac{f(e_{i_1,j_1})}{f(e_{i_2,j_2})}e_{i_2,j_2+(j-j_1)}\right) = f(e_{i_1,j}) - \frac{f(e_{i_1,j_1})}{f(e_{i_2,j_2})}f(e_{i_2,j_2+(j-j_1)}).$$

Clearly (by design), this expression is zero when  $j = j_1$ . And for  $j < j_1$ , we have  $f(e_{i_1,j}) = f(e_{i_2,j_2+(j-j_1)}) = 0$ , so it is zero then as well. Hence the measure  $S$  of this new basis is smaller, as desired.  $\square$

**Lemma 3.5.** *For any  $n$  and linear  $f : \mathbb{C}^n \rightarrow \mathbb{C}$ , there is a Jordan basis  $e_j$  for  $J_n$  such that there is at most one  $j$  with  $f(e_j) \neq 0$ .*

*Proof.* Let  $e_j$  be a Jordan basis for  $J_n$ . If  $\{j : f(e_j) \neq 0\}$  is the empty set, we are done. Otherwise, let  $j_0 = \min\{j : f(e_j) \neq 0\}$ . For any Jordan basis  $f_j$  with  $j_0 = \min\{j : f(e_j) \neq 0\}$ , define

$$S((f_j)_j) := \begin{cases} -1, & \{j > j_0 : f(e_j) \neq 0\} = \emptyset \\ n - \min\{j > j_0 : f(e_j) \neq 0\}, & \text{otherwise} \end{cases}.$$

We proceed by induction on  $S$ . That is, let  $(e_j)_j$  be a Jordan basis for  $J_n$  with  $j_0 = \min\{j : f(e_j) \neq 0\}$ . Our inductive hypothesis is that if there exists a Jordan basis  $(e'_j)_j$  with  $j_0 = \min\{j : f(e'_j) \neq 0\}$  and  $S((e'_j)_j) < S((e_j)_j)$ , then the conclusion holds.

We have two cases: either  $(e_j)_j$  satisfies the desired property, or not. If not, then let  $j_1 = \min\{j > j_0 : f(e_j) \neq 0\}$ , and define a new Jordan basis  $e'_j$  as follows.

- $e'_n := e_n - \frac{f(e_{j_1})}{f(e_{j_0})}e_{n-(j_1-j_0)}$
- For  $j < n$ ,  $e'_j := J_n^{n-j}e'_n$

It is straightforward to check that  $j_0 = \min\{j : f(e_j) \neq 0\}$ , and that  $S((e'_j)_j) \leq S((e_j)_j) - 1$ . By our inductive hypothesis, we are done.  $\square$

**Theorem 3.6.** *For any finite-dimensional  $V$ , nilpotent  $A : V \rightarrow V$ , and linear  $f : V \rightarrow \mathbb{C}$ , there is a Jordan basis  $e_{ij}$  for  $A$  such that there is at most one pair  $(i, j)$  with  $f(e_{ij}) \neq 0$ .*

*Proof.* Lemma 3.4 provides a Jordan basis  $e_{ij}$  such that for all  $i \neq i_0$  and all  $j$ , we have  $f(e_{ij}) = 0$ . Restricting  $A$  to  $\langle e_{i_0j} \rangle_j$  arbitrary gives a Jordan block, and then applying Lemma 3.5 gives the desired result.  $\square$

## 4 Finding $\mathfrak{sl}_2$ -triples $(E, H, F)$ in $\mathfrak{gl}_{m+n}$ with a particular $E$ .

Let

$$e = \begin{pmatrix} 0 & & & \\ 1 & 0 & & \\ & 1 & \ddots & \\ & & \ddots & 0 \\ & & & 1 & 0 \end{pmatrix} \in \mathfrak{gl}_n,$$

and let  $E = \begin{pmatrix} 0 & 0 \\ 0 & e \end{pmatrix} \in \mathfrak{gl}_{m+n}$ . We will show that there is exactly one  $\mathfrak{sl}_2$ -triple  $(E, H, F)$ , and we will find what it looks like. First we solve the case  $m = 0$  (so  $E = e$ ), and then we use this to solve the case of arbitrary  $m$ .

**Lemma 4.1.** *There is exactly one way to choose  $h, f \in \mathfrak{gl}_n$  so that  $(e, h, f)$  is an  $\mathfrak{sl}_2$ -triple.*

*Proof.* Note that  $[h', e'] = 2e'$ , and  $[e', f'] = h'$ , and  $[h', f'] = -2f'$ . Thus  $e, h, f$  must obey the same relations. In particular,  $he - eh = 2e$ . The matrix  $eh$  is  $h$  shifted down one, and  $he$  is  $h$  shifted left one. Thus,  $2e_{ij} = (he - eh)_{ij} = h_{i,j+1} - h_{i-1,j}$ . We can use this to show that  $h_{ij} = 0$  when  $i \neq j$ . Then we can use it to show that  $h_{ii} = h_{i-1,i-1} + 2$ , so that  $h_{ii} = h_{11} + 2(i-1)$ .

Similarly, from  $[e, f] = h$  we get that  $h_{ij} = (ef - fe)_{ij} = f_{i-1,j} - f_{i,j+1}$ . We can use this to show that  $f_{ij} = 0$  when  $j \neq i+1$ . Then we can use it to show that  $f_{i,i+1} = f_{i+1,i+2} + h_{i+1,i+1}$ , that  $f_{1,2} = -h_{1,1}$ , and that  $f_{n-1,n} = h_{n,n}$ . From the first equation we find that

$$-h_{1,1} = f_{1,2} = f_{n-1,n} + \sum_{i=1}^{n-1} h_{ii} = \sum_{i=1}^n h_{ii} \implies \sum_i h_{ii} = 0.$$

Remark: this is just the statement that  $h \in \mathfrak{sl}_n$ ; in other words, we will see that every choice of  $\mathfrak{sl}_2$ -triple in  $\mathfrak{gl}_{m+n}$  is also an  $\mathfrak{sl}_2$ -triple in  $\mathfrak{sl}_{m+n}$ . This shows that  $h_{11} = n-1, h_{22} = n-3, \dots, h_{nn} = 1-n$ . So we have determined

$h$ ; it is

$$h = \begin{pmatrix} n-1 & & & & \\ & n-3 & & & \\ & & \ddots & & \\ & & & 3-n & \\ & & & & 1-n \end{pmatrix}.$$

Now, we can use our expression for  $f$  in terms of  $h$  to obtain

$$f = \begin{pmatrix} 0 & 1-n & & & \\ & 0 & (1-n) + (3-n) & & \\ & & \ddots & \ddots & \\ & & & 0 & (1-n) + \cdots + (n-1) \\ & & & & 0 \end{pmatrix} =$$

$$\begin{pmatrix} 0 & 1(1-n) & & & \\ & 0 & 2(2-n) & & \\ & & 0 & (n-2)(-2) & \\ & & & 0 & (n-1)(-1) \\ & & & & 0 \end{pmatrix}.$$

□

**Lemma 4.2.** *There is exactly one way to choose  $H, F \in \mathfrak{gl}_{m+n}$  so that  $(E, H, F)$  is an  $\mathfrak{sl}_2$ -triple.*

*Proof.* Suppose we have  $H, F$  so that  $(E, H, F)$  is an  $\mathfrak{sl}_2$ -triple. Writing  $F =: \begin{pmatrix} F_{11} & F_{12} \\ F_{21} & f \end{pmatrix}$ , and similarly for  $H$ , we have

$$2E = [H, E] = \begin{pmatrix} 0 & H_{12}e \\ 0 & he \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ eH_{21} & eh \end{pmatrix},$$

$$H = [E, F] = \begin{pmatrix} 0 & 0 \\ eF_{21} & ef \end{pmatrix} - \begin{pmatrix} 0 & F_{12}e \\ 0 & fe \end{pmatrix}.$$

From these we observe that  $(e, h, f)$  must also be an  $\mathfrak{sl}_2$ -triple, so  $h, f$  must be as in Lemma 4.1. We also see that  $H_{11} = 0$ . Recalling that left multiplication by  $e$  is a down-shift, and right multiplication is a left-shift, we see that  $H_{12}$



is all zeroes except for the leftmost column, and  $H_{21}$  is all zeroes except for the bottom row. Then our final constraint is that

$$-2F = [H, F] =$$

$$\begin{pmatrix} H_{12}F_{21} & H_{12}F_{22} \\ H_{21}F_{11} + H_{22}F_{21} & H_{21}F_{12} + H_{22}F_{22} \end{pmatrix} - \begin{pmatrix} F_{12}H_{21} & F_{11}H_{12} + F_{12}H_{22} \\ F_{22}H_{21} & F_{21}H_{12} + F_{22}H_{22} \end{pmatrix}.$$

Now  $H_{12} = F_{12}e$ , and  $H_{21} = eF_{21}$ , from the equation  $H = [E, F]$ . Substituting in the equation above then,

$$\begin{aligned} -2F &= \begin{pmatrix} F_{12}eF_{21} & F_{12}ef \\ eF_{21}F_{11} + hF_{21} & eF_{21}F_{12} + hf \end{pmatrix} - \begin{pmatrix} F_{12}eF_{21} & F_{11}F_{12}e + F_{12}h \\ feF_{21} & F_{21}F_{12}e + fh \end{pmatrix} = \\ &= \begin{pmatrix} 0 & F_{12}(fe + h) \\ eF_{21}F_{11} + hF_{21} & eF_{21}F_{12} + hf \end{pmatrix} - \begin{pmatrix} 0 & F_{11}F_{12}e + F_{12}h \\ (ef - h)F_{21} & F_{21}F_{12}e + fh \end{pmatrix} = \\ &= \begin{pmatrix} 0 & F_{12}fe \\ eF_{21}F_{11} & eF_{21}F_{12} + hf \end{pmatrix} - \begin{pmatrix} 0 & F_{11}F_{12}e \\ efF_{21} & F_{21}F_{12}e + fh \end{pmatrix}. \end{aligned}$$

Now we see that  $F_{11} = 0$ , and consequently that  $F_{12} = F_{21} = 0$  as well. This shows that  $H_{12} = H_{21} = 0$ . We conclude that  $H$  and  $F$  just have  $h$  and  $f$  in their bottom-right corners, respectively.  $\square$

## 5 Finding the Slodowy slices with the same $E$

First we find  $\ker \text{ad}_f$ . We have  $(fX)_{ij} = i(n-i)A_{i+1,j}$ , and  $(Xf)_{ij} = (j-1)(n-(j-1))A_{i,j-1}$ . So, for all  $i, j \in \{1, \dots, n\}$ , we have

$$i(n-i)A_{i+1,j} = (j-1)(n-(j-1))A_{i,j-1}.$$

Taking  $j = 1$ , we find that  $A_{i,1} = 0$  for  $i \geq 2$ . Then, taking  $j > 1$ , we find that for  $i, j \in \{1, \dots, n-1\}$ ,

$$A_{i+1,j+1} = \frac{(j-1)(n-(j-1))}{i(n-i)}A_{ij}.$$

So,  $\ker \text{ad}_f$  is the set of matrices which are upper triangular and satisfy the above condition.

To find the Slodowy slice associated to the previous  $\mathfrak{sl}_2$ -triple  $(E, H, F)$ , we just need to find  $\ker \operatorname{ad}_F$ . We have

$$[F, X] = \begin{pmatrix} 0 & 0 \\ fX_{21} & fX_{22} \end{pmatrix} - \begin{pmatrix} 0 & X_{12}f \\ 0 & X_{22}f \end{pmatrix}.$$

Thus,  $X_{21}$  must be all zeroes except for the first row, and  $X_{12}$  must be all zeroes except for the last column, and  $X_{22} \in \ker \operatorname{ad}_f$ . There is no restriction on  $X_{11}$ . This describes  $\ker \operatorname{ad}_F$ .

For  $X \in \mathcal{S}_{m,n}$ , define  $u(X) := X_{11}$ .

### 5.1 Finding $\tilde{\mathcal{N}}_{m,n}$

Let  $\mathcal{N}_m \subseteq \mathfrak{gl}_m$  be the nilpotent elements. Let  $\mathcal{S}'_{m,n}$  be the set of  $X \in \mathcal{S}_{m,n}$  such that both  $X$  and  $u(X)$  are nilpotent. Let  $\tilde{\mathcal{N}}_{m,n} = \{(\mathfrak{b}, X) : X \in \mathfrak{b}\} \subseteq \mathcal{B}_{m+n} \times \mathcal{S}'_{m,n}$ . Define  $\pi_{m,n} : \tilde{\mathcal{N}}_{m,n} \rightarrow \mathcal{N}_m$  by  $(\mathfrak{b}, X) \mapsto X_{11}$ . For  $Y \in \mathfrak{gl}_m$ , we call  $\pi_{m,n}^{-1}(Y)$  the *Springer fiber at the  $n$ -Slodowy slice at  $Y$* .

**Lemma 5.1.** *Let  $J$  be a jordan block with zeroes along the diagonal, and let  $A$  be upper triangular and nonzero. Then  $J + A$  is not nilpotent.*

*Proof.* It is straightforward to show by induction that if  $v_i = 0$  for  $i < j$ , and  $v_j \neq 0$ , then  $((J + A)^k v_j)_{j+k} = v_j$ . Let  $i$  be such that  $Ae_i \neq 0$ . Then  $(J + A)^{i-1}e_1$  has nonzero  $e_i$ -component. Then  $(J + A)^i e_1$  has some nonzero  $e_{i'}$ -component for some  $i' \leq i$ . Then  $(J + A)^{i+(n-i')}e_1$  has some nonzero  $e_n$ -component. And  $i + (n - i') \geq n$ , so we're done.  $\square$

**Lemma 5.2.** *Let  $X \in \mathfrak{gl}_m$ , and let*

$$Y = \begin{pmatrix} y_{11} & y_{12} & y_{13} & \cdots & y_{1,n-1} & y_{1n} \\ d_1 & y_{22} & y_{23} & \cdots & y_{2,n-1} & y_{2n} \\ & d_2 & y_{33} & \cdots & y_{3,n-1} & y_{3n} \\ & & \ddots & \cdots & \vdots & \vdots \\ & & & d_{n-2} & y_{n-1,n-1} & y_{n-1,n} \\ & & & & d_{n-1} & y_{nn} \end{pmatrix} \in \mathfrak{gl}_n.$$

For any  $a, b \in \mathbb{C}^m$ ,

$$\det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ b \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & Y \end{array} \right) =$$

$$\det X \det Y + \left( \prod_i d_i \right) \det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ b \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & 0 \end{array} \right)$$

*Proof.* By induction on  $n$ . In the case  $n = 1$ , expanding along the last row (taking the usual interpretation of the empty product) gives the desired result.

Now suppose  $n > 1$ . Expanding along the last row, we get

$$d_{n-1} \det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ b \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & Y_{n,n-1} \end{array} \right) - y_{nn} \det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ | \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & Y_{n,n} \end{array} \right).$$

Using our inductive hypothesis for the first determiniant, and using that  $\det \left( \begin{array}{c|c} A_{11} & 0 \\ \hline A_{21} & A_{22} \end{array} \right) = \det A_{11} \det A_{22}$  for the second, the expression becomes

$$d_{n-1} \left( \det X \det Y_{n,n-1} + \left( \prod_{i \leq n-2} d_i \right) \det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ b \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & 0 \end{array} \right) \right) - y_{nn} \det X \det Y_{nn} =$$

$$(d_{n-1} Y_{n,n-1} - y_{nn} \det Y_{nn}) \det X + \left( \prod_i d_i \right) \det \left( \begin{array}{c|c} X & \begin{array}{c} | \\ b \\ | \end{array} \\ \hline \begin{array}{c} - & a & - \end{array} & 0 \end{array} \right) =$$

$$\det Y \det X + \left( \prod_i d_i \right) \det \left( \begin{array}{ccc|c} & & & b \\ & & & | \\ & & & | \\ \hline - & a & - & 0 \end{array} \right).$$

□

**Corollary 5.3.** *If  $X$  is nilpotent, and*

$$\left( \begin{array}{ccc|c} & & & b \\ & & & | \\ & & & | \\ \hline - & a & - & \\ & & & Y \end{array} \right)$$

*is nilpotent as well, then  $Y$  is nilpotent (TODO: and that other determinant is zero).*

*Proof.* By the previous lemma, the characteristic polynomial of the big matrix is

$$g_X(\lambda)g_Y(\lambda) + f(\lambda),$$

where  $g_X(\lambda) = \lambda^m$  is the characteristic polynomial of  $X$ , and  $f(\lambda)$  is some polynomial of degree at most  $m - 1$ . □

Now, taking the previous corollary and the first lemma together, we see that

$$\mathcal{S}'_{m,n} = \left\{ \left( \begin{array}{ccc|cccc} & & & & & & b \\ & & & & & & | \\ & & & & & & | \\ \hline - & a & - & 0 & & & \\ & & & 1 & 0 & & \\ & & & & & \ddots & \\ & & & & & & \ddots & \\ & & & & & & & 1 & 0 \end{array} \right) : a, b \in \mathbb{C}^m, X \in \mathfrak{gl}_m \text{ is nilpotent} \right\}.$$

## 6 Simplifying the definition of a Springer fiber at a Slodowy slice

Let  $\mathcal{N}_m \subseteq \mathfrak{gl}_m(\mathbb{C})$  be the subset consisting of nilpotent elements. For  $X \in \mathcal{N}_m$  and  $a, b \in \mathbb{C}^m$ , let

$$A_{X,a,b} = \left( \begin{array}{c|ccc} X & & & & b \\ \hline - & a & - & & \\ \hline & & 0 & & \\ & & 1 & 0 & \\ & & & 1 & \ddots \\ & & & & \ddots & 0 \\ & & & & & 1 & 0 \end{array} \right) \in \mathfrak{gl}_{m+n}(\mathbb{C}).$$

By the definition given in the previous section, we have

$$\tilde{\mathcal{N}}_{m,n} = \{(\mathfrak{b}, X) : X \in \mathfrak{b}\} \subseteq \mathcal{B}_{m+n} \times \mathcal{S}'_{m,n},$$

and the Springer fiber at the  $n$ -Slodowy slice at a nilpotent  $X \in \mathfrak{gl}_m$  is

$$\begin{aligned} \pi_{m,n}^{-1}(X) &= \{(\mathfrak{b}, A_{X,a,b}) : A_{X,a,b} \in \mathfrak{b}, A_{X,a,b} \in \mathcal{S}'_{m,n}\} \\ &= \{(\mathfrak{b}, A_{X,a,b}) : A_{X,a,b} \in \mathfrak{b}, A_{X,a,b} \text{ nilpotent}\} \\ &\cong \{(\mathfrak{b}, a, b) : A_{X,a,b} \in \mathfrak{b}, A_{X,a,b} \text{ nilpotent}\}. \end{aligned}$$

Using our correspondence between  $\mathcal{B}_{m+n}$  and complete flags of  $\mathbb{C}^{m+n}$ , we obtain

$$\pi_{m,n}^{-1}(X) \cong \{(V, a, b) : \forall i. A_{X,a,b} V_i \subseteq V_{i-1}\}.$$

## 7 Strategy and setup for finding the irreducible components of a Springer fiber at a Slodowy slice

Fix any  $X \in \mathcal{N}$ . As we have fixed  $X$ , we now write  $A_{a,b} := A_{X,a,b}$ . Let  $(e_{ij})_{1 \leq i \leq k, 1 \leq j \leq \lambda_i}$  be a Jordan basis for  $X$ . For convenience we define  $e_{i0} := 0$ ;

now we may express the fact that  $(e_{ij})$  is a Jordan basis by writing  $\forall i. Xe_{ij} = e_{i,j-1}$ .

In this section we find the irreducible components of

$$\pi^{-1}(X) \cong V := \{(A_{a,b}, U) : \forall i. A_{a,b}U_{i+1} \subseteq U_i\}.$$

For  $1 \leq w \leq k$  and  $0 \leq r \leq \lambda_w$  (note that we allow  $r = 0$ ), define

$$V_{w,r} := \{(A_{a,b}, U) \in V : \exists P \in \text{GL}_m. \exists b'. (P^{-1}, I_n)A_{a,b}(P, I_n) = A_{e_{wr}, b'}\}.$$

**Lemma 7.1.**  $V = \bigcup_{1 \leq w \leq k, 0 \leq r \leq \lambda_w} V_{w,r}$ . Further,  $V_{w_1 r_1} = V_{w_2 r_2}$  exactly when either  $r_1 = r_2 = 0$ , or  $\lambda_{w_1} = \lambda_{w_2} \wedge r_1 = r_2$ . When  $V_{w_1 r_1} \neq V_{w_2 r_2}$ , we have  $V_{w_1 r_1} \cap V_{w_2 r_2} = \emptyset$ .

*Proof.* TODO □

Now, fix any  $w$  and  $r$ . We will find the irreducible components of  $V_{w,r}$ . These will all happen to be equidimensional (with dimensions independent of  $w$  and  $r$ ), so their closures in  $V$  will be the irreducible components of  $V$ .

Let

$$G := \{P \in \text{GL}_m : P^{-1}XP = X\},$$

and

$$G_{wr} = \{A \in G : e_{wr}A = e_{wr}\}.$$

Now, define

$$U_{wr} = \{(A_{e_{wr}, b}, U) \in V_{wr}\}.$$

Let  $G$  act on  $V_{wr}$  by

$$P \cdot (A_{e_{wr}, b}, U) := ((P, I_n)A_{e_{wr}, b}(P, I_n)^{-1}, (P, I_n)U) = (A_{e_{wr}P^{-1}, Pb}, (P, I_n)U).$$

Consider the map  $\varphi : U_{wr} \times G \rightarrow V_{wr}$  defined by

$$(x, P) \mapsto P \cdot x.$$

By restriction of  $G$  to  $G_{wr}$  and  $V_{wr}$  to  $U_{wr}$ , we obtain an action of  $G_{wr}$  on  $U_{wr}$ . Then, letting  $G_{wr}$  act on  $G$  by  $g \cdot h := hg^{-1}$ , we obtain an action of  $G_{wr}$  on  $U_{wr} \times G$ .

**Lemma 7.2.** *As an algebraic variety,  $G$  is irreducible.*

*Proof.* It's just  $\mathbb{C}^{\text{something}}$ , since its blocks are the lower-left-toeplitz matrices.  $\square$

**Lemma 7.3.** *The map  $\varphi$  is a principal  $G_{wr}$ -bundle.*

*Proof.* We need to show that  $G_{wr}$  acts freely and transitively on the fibers of  $\varphi$ . It is obvious that  $G_{wr}$  acts freely on  $U_{wr} \times G$ ; it is enough to note that it acts freely on  $G$ .

Let  $y \in V_{wr}$ . By definition of  $V_{wr}$ , there is  $P_y \in G$  with  $P_y \cdot y \in U_{wr}$ . We have

$$\begin{aligned} \varphi^{-1}(y) &= \{(x, P) : P \cdot x = y\} = \\ &= \{(P^{-1}y, P) : P^{-1}y \in U_{wr}\} = \\ &= \{((P^{-1}P_y^{-1}) \cdot (P_y \cdot y), P) : (P^{-1}P_y^{-1}) \cdot (P_y \cdot y) \in U_{wr}\}. \end{aligned}$$

For any  $x \in U_{wr}$  (in particular for  $x = P_y \cdot y$ ), we have  $G_{wr} = \{g \in G : g \cdot x \in U_{wr}\}$ . Therefore, the fiber above becomes

$$\{((P^{-1}P_y^{-1}) \cdot (P_y \cdot y), P) : (P^{-1}P_y^{-1}) \in G_{wr}\}.$$

Setting  $Q := P^{-1}P_y^{-1}$ , so that  $P = P_y^{-1}Q^{-1}$ , the above becomes

$$\begin{aligned} \{(Q \cdot (P_y \cdot y), P_y^{-1}Q^{-1}) : Q \in G_{wr}\} = \\ \{Q \cdot (P_y \cdot y, P_y^{-1}) : Q \in G_{wr}\}. \end{aligned}$$

We see that the fibers are exactly the  $G_{wr}$ -orbits; or in other words,  $G_{wr}$  acts transitively on the fibers, as desired.  $\square$

Our strategy is to find the irreducible components  $X \subseteq U_{wr}$ , and we will then argue that the irreducible components of  $V_{wr}$  are of the form  $\varphi(X \times G)$ . So, we will now find the irreducible components of  $U_{wr}$ .

Actually this will be unnecessarily difficult to think about; it is easiest in the case  $r = 0$ . So, we will change basis to make  $r = 0$ . Let  $\lambda' = (\lambda_1, \dots, \lambda_{w-1}, \lambda_w - r, \lambda_{w+1}, \dots, \lambda_k)$ . Let  $X'$  be in Jordan normal form with shape  $\lambda'$ . Let  $U'_{wr} = \{(A_{X',0,b}, U) : \forall i. A_{X',0,b}U_{i+1} \subseteq U_i\}$ . Let  $e'_{ij}$  be a Jordan basis for  $X'$ . Let  $f_1, \dots, f_n$  be a Jordan basis for the restriction of  $A_{X,0,b}$  to  $\dots$ . Set  $m' := m - r$ , and  $n' := n + r$ . Let  $f'_1, \dots, f'_{n'}$  blah. Define the linear map  $Q_{wr} : \mathbb{C}^{m'+n'} \rightarrow \mathbb{C}^{m+n}$  by:

- For all  $i$ ,  $e'_{ij} \mapsto e_{ij}$ .

- For  $j = 1, \dots, r$ ,  $f'_{n+j} \mapsto e_{w,(\lambda_w-r)+j}$ .
- For  $j = 1, \dots, n$ ,  $f'_j \mapsto f_j + e_{w,(\lambda_w-r)-n+j}$ .

Observe that conjugation by  $Q_{wr}$  maps  $U_{wr}$  to  $U'_{wr}$ , and conjugation by  $Q_{wr}^{-1}$  maps  $U'_{wr}$  to  $U_{wr}$ . We conclude that  $U_{wr} \cong U'_{wr}$ ; so to find the irreducible components of  $U_{wr}$  we just need to find the irreducible components of  $U'_{wr}$ . To clear the context, which is rather cluttered by now, and to avoid writing primes everywhere, we move to a new section.

## 8 Finding the irreducible components of $U_0$

### 8.1 Setup

Let  $X$  be nilpotent with Jordan basis  $(e'_{ij})_{1 \leq i \leq k, 1 \leq j \leq \lambda'_i}$ . Let  $V = \{(A_{a,b}, U) : \forall i. A_{a,b}U_{i+1} \subseteq U\}$ . Let

$$U_0 = \{(A_{0,b}, U) \in V\}.$$

We will find the irreducible components of  $U_0$ .

We write  $b_{ij}$  to denote the projection of  $b \in \mathbb{C}^m$  onto  $e_{ij}$ . For each row  $i$ , let  $p_i(b) = \max\{j : b_{ij} \neq 0\}$  (the maximum of the empty set is zero). Then set  $q_i(b) = \lambda_i - p_i(b)$ . When it is clear enough from context, we will just write  $p_i$  and  $q_i$  instead of  $p_i(b)$  and  $q_i(b)$ .

Let  $I = \{i_1 < \dots < i_r\} \subseteq \{1, \dots, k\}$ , and let  $(\rho_i)_{i \in I}$  be any map  $I \rightarrow \mathbb{N}_{>0}$  such that (1)  $\rho_i \leq \lambda_i$ , (2)  $\rho_i$  is decreasing with  $i$ , (3)  $\lambda_i - \rho_i$  is decreasing with  $i$ , and (4)  $\rho_i < n$ . For notational convenience (although we assign meaning to neither  $i_0$  nor  $i_{r+1}$ ), we define  $q_{i_0} := n$ , and  $p_{i_{r+1}} := 0$ . Then, we define  $B_{I,(\rho_i)}$  as the set of  $b \in \mathbb{C}^m$  satisfying the following conditions.

- For all  $k \in \{1, \dots, r\}$ ,  $p_i = \rho_i$ .
- For all  $k \in \{0, \dots, r\}$ ,  $p_{i_{k+1}} = \max_{i: q_i < q_{i_k}} p_i$ .

Note that for any  $b \in B_{I,(\rho_i)}$  we have  $p_{i_1} > \dots > p_{i_r} > p_{i_{r+1}}$ , and also  $q_{i_0} > q_{i_1} > \dots > q_{i_r}$ .

Let  $U_{I,(\rho_i)} := \{(A_{0,b}, U) \in V : b \in B_{I,(\rho_i)}\}$ . The idea here is to show that blah relation holds between U and B.



**Lemma 8.1.**  $\mathbb{C}^m = \bigcup_{I, (\rho_i)} B_{I, (\rho_i)}$ , where  $I$  ranges over all subsets of  $\{1, \dots, k\}$ , and  $(\rho_i)$  ranges over all maps  $I \rightarrow \mathbb{N}_{>0}$  satisfying the conditions (1), (2), (3), (4). Further, none of the  $B_{I, (\rho_i)}$  is contained in the union of the others.

*Proof.* Let  $b \in \mathbb{C}^m$ . If  $\{i : q_{i_0} > q_i\}$  is the empty set, then stop. Otherwise, take any  $i_1 \in \arg \max_{i: q_{i_0} > q_i} p_i$ , and set  $\rho_{i_1} := p_{i_1}$ . If  $\{i : q_{i_1} > q_i\} = \emptyset$ , then stop. Otherwise, take any  $i_2 \in \arg \max_{i: q_{i_1} > q_i} p_i$ , and set  $\rho_{i_2} := p_{i_2}$ . Continuing on in this way, eventually we reach a point where  $\{i : q_{i_k} > q_i\} = \emptyset$ . Then we set  $I = \{i_1, \dots, i_k\}$ . Note that  $I, (\rho_i)$  satisfy conditions (1)–(4), and furthermore  $b \in B_{I, (\rho_i)}$ .

Now, we show that no  $B_{I, (\rho_i)}$  is contained in the union of the others. Indeed, fix  $I$  and  $(\rho_i)$ . Take any  $b \in B_{I, (\rho_i)}$  with  $p_i = \rho_i$  for  $i \in I$  and  $p_i = 0$  for  $i \notin I$ . It is clear that  $b \notin B_{I', (\rho'_i)}$  whenever  $I' \neq I$  or  $(\rho'_i) \neq (\rho_i)$ .  $\square$

## 8.2 A study of $B_{I, (\rho_i)}$

Fix any  $I$  and  $(\rho_i)$  satisfying the conditions (1)–(4). As before, we write  $\{i_1 < \dots < i_r\} := I$ , and  $q_{i_0} := n$ , and  $p_{i_{r+1}} := 0$ .

First, we provide an alternative characterization of  $B_{I, (\rho_i)}$ .

**Lemma 8.2.**  $B_{I, (\rho_i)}$  is the set of  $b \in \mathbb{C}^m$  satisfying the following conditions.

- For all  $k \in \{1, \dots, r\}$ ,  $p_{i_k} = \rho_{i_k}$ .
- For all  $i \notin I$ ,
  - For all  $k \in \{0, \dots, r\}$  such that  $\lambda_i > q_{i_k} + p_{i_{k+1}}$ , we have  $q_{i_k} \leq q_i$ .
  - For all  $k \in \{1, \dots, r+1\}$  such that  $\lambda_i \leq q_{i_{k-1}} + p_{i_k}$ , we have  $p_i \leq p_{i_k}$ .

*Proof.* First we show that every element of  $B_{I, (\rho_i)}$  satisfies those conditions. Let  $b \in B_{I, (\rho_i)}$ . It is clear that  $\forall k. p_{i_k} = \rho_{i_k}$ .

Take  $i \notin I$  and  $k \in \{0, \dots, r\}$  such that  $\lambda_i > q_{i_k} + p_{i_{k+1}}$ . Suppose for contradiction that  $q_i < q_{i_k}$ . Then  $p_i \leq \max_{j: q_j < q_{i_k}} p_j = p_{i_{k+1}}$ . Then  $\lambda_i = p_i + q_i < q_{i_k} + p_{i_{k+1}}$ , a contradiction. So we must have  $q_{i_k} \leq q_i$ , as desired.

Now take  $i \notin I$  and  $k \in \{1, \dots, r+1\}$  such that  $\lambda_i \leq q_{i_{k-1}} + p_{i_k}$ . Suppose for contradiction that  $p_i > p_{i_k}$ . Then, putting this together with the first inequality,  $\lambda_i - p_i < q_{i_{k-1}} + p_{i_k} - p_{i_k}$ ; that is,  $q_i < q_{i_{k-1}}$ . Consequently,  $p_i \leq \max_{j: q_j < q_{i_{k-1}}} p_j = p_{i_k}$ , as desired.

Now we have shown that every element of  $B_{I, (\rho_i)}$  satisfies the conditions of the lemma, and we proceed to the converse. Let  $b \in \mathbb{C}^m$  satisfy the

conditions. Let  $k \in \{0, \dots, r\}$ . We need to show that  $\max_{j: q_j < q_{i_k}} p_j = p_{i_{k+1}}$ . Given the conditions (1)–(4) on  $\rho_i$ , it suffices to show that for each  $i \notin I$  with  $q_i > q_{i_k}$ , we have  $p_i \leq p_{i_{k+1}}$ . Indeed, given  $i \notin I$  with  $q_i > q_{i_k}$ , we cannot have  $\lambda_i > q_{i_k} + p_{i_{k+1}}$ , as that would imply that  $q_{i_k} \leq q_i$ . Hence we must have  $\lambda_i \leq q_{i_{k-1}} + p_{i_k}$ , and consequently  $p_i \leq p_{i_k}$ .  $\square$

**Corollary 8.3.**  $B_{I,(\rho_i)}$  is the set of  $b \in \mathbb{C}^m$  satisfying the following conditions.

- For all  $k \in \{1, \dots, r\}$ ,  $p_{i_k} = \rho_{i_k}$ .
- For  $i \notin I$ ,
  - If  $\lambda_i \geq q_{i_0} + p_{i_1}$ , then  $p_i \leq \lambda_i - q_{i_0}$ .
  - If there is  $k \in \{0, \dots, r\}$  with  $q_{i_{k-1}} + p_{i_k} > \lambda_i \geq q_{i_k} + p_{i_{k+1}}$ , then  $p_i \leq \min(p_{i_k}, \lambda_i - q_{i_k})$ .
  - If  $q_{i_r} + p_{i_{r+1}} > \lambda_i$ , then  $p_i \leq p_{i_{r+1}}$ .

*Proof.* Both  $q_{i_k}$  and  $p_{i_k}$  are decreasing as  $k$  increases, so this follows directly from Lemma 8.2. (Note that  $p_i \leq \lambda_i - q_{i_k}$  iff  $q_{i_k} \leq q_i$ .)  $\square$

**Corollary 8.4.**

$$B_{I,(\rho_i)} \cong \prod_{k=1}^r (\mathbb{C}^{\rho_{i_k}-1} \times (\mathbb{C} \setminus \{0\})) \times \prod_{i: \lambda_i \geq q_{i_0} + p_{i_1}} \mathbb{C}^{\lambda_i - q_{i_0}} \times \prod_{k=0}^r \prod_{\{i \notin I: q_{i_{k-1}} + p_{i_k} > \lambda_i \geq q_{i_k} + p_{i_{k+1}}\}} \mathbb{C}^{\min(p_{i_k}, \lambda_i - q_{i_k})}$$

*Proof.* Here I use the notation  $x \times y = (x, y)$ , and so on. The isomorphism sends  $b \in B_{I,(\rho_i)}$  to

$$\begin{aligned} & \prod_{k=1}^r (b_{i_k 1}, \dots, b_{i_k \rho_{i_k}}) \times \prod_{i: \lambda_i \geq q_{i_0} + p_{i_1}} (b_{i 1}, \dots, b_{i, \lambda_i - q_{i_0}}) \times \\ & \prod_{k=0}^r \prod_{\{i \notin I: q_{i_{k-1}} + p_{i_k} > \lambda_i \geq q_{i_k} + p_{i_{k+1}}\}} (b_{i 1}, \dots, b_{i, \min(p_{i_k}, \lambda_i - q_{i_k})}). \end{aligned}$$

Corollary 8.3 tells us that this is an isomorphism.  $\square$

**Corollary 8.5.**

$$\dim B_{I,(\rho_i)} = \sum_{i: \lambda_i \geq q_{i_0} + \rho_{i_1}} (\lambda_i - q_{i_0}) + \sum_{k=0}^r \sum_{\{i: q_{i_{k-1}} + p_{i_k} > \lambda_i \geq q_{i_k} + p_{i_{k+1}}\}} \min(p_{i_k}, \lambda_i - q_{i_k}).$$

*Proof.* Immediate from Corollary 8.4.  $\square$

### 8.3 A study of $U_{I,(\rho_i)}$

Fix any  $I$  and  $(\rho_i)$  satisfying the conditions of Lemma 8.1. We will find the irreducible components of  $U_{I,(\rho_i)}$ , and show that their closures are in fact irreducible components of  $U_0$ .

I claim that  $A_{0,b}$  has the same shape for every  $(A_{0,b}, U) \in U_{I,(\rho_i)}$ . Call this shape  $\mu$ . By finding a algebraic map taking  $b$  to a Jordan basis for  $A_{0,b}$ , we will put  $U_{I,(\rho_i)}$  in isomorphism with the product (choice of  $b$ )  $\times$  (Springer fiber at  $J(\mu)$ ). Then we will use our result about the usual Springer fiber at  $J(\mu)$  to find the irreducible components of  $U_{I,(\rho_i)}$ .

So, now we find a Jordan basis for  $A_{0,b}$ .

**Lemma 8.6.** *Let  $P = \max_{i \in I} \rho_i$ , and for  $i \in I$ , let  $P_i = \max_{j \in I: j > i} \rho_j$ . The following vectors give a Jordan basis for  $A_{0,b}$ . (For convenience, we write  $A := A_{0,b}$  in this lemma and proof.)*

- For  $i \notin I$ , the chain of length  $p_i + q_i$  beginning with  $e_{i,p_i+q_i}$
- The chain of length  $n + P$  beginning with  $f_n - (A^{n+P} f_n \gg n + P)$
- For  $i \in I$ , the chain of length  $q_i + P_i$  beginning with  $v_i - (A^{q_i+P_i} v_i \gg q_i + P_i)$ , where  $v_i := A^{n-q_i} f_n - \sum_{l=1}^{p_i} b_{il} e_{i,l+q_i}$

*Proof.* There are three things to check: (1) the chains are no longer than their claimed lengths, (2) the claimed lengths sum to  $m + n$ , and (3) the span of the chains is  $\mathbb{C}^{m+n}$ .

We have defined  $P$  and  $P_i$  in terms of the  $\rho_i$  to make it clear that they only depend on  $I$  and the  $\rho_i$ . Now we provide more useful characterizations. It is immediate from the definition of  $U_{I,(\rho_i)}$  that  $P = \max_{l: q_l < n} p_l$ , and  $P_i = \max_{l: q_l < q_i} p_l$ .

*Proof of (1).* It is obvious that a chain beginning with  $e_{i,p_i+q_i}$  has length  $p_i + q_i$ .

Now consider the chain beginning with  $f_n - (A^{n+P} f_n \gg n + P)$ . Note that  $A^n f_n = b$ , so  $A^{n+P} f_n = A^P b = b \ll P$ . By shifting  $b$  left  $P$  times, we zero out all the rows  $i$  where  $q_i < n$ . This ensures that the operation of shifting  $b \ll P$  right  $n + P$  times is invertible by shifting left  $n + P$  times. That is,

$$A^{n+P} f_n = b \ll P = ((b \ll P) \gg n + P) \ll n + P = A^{n+P} (A^{n+P} f_n \gg n + P).$$

This shows that the chain has length at most  $n + P$ , as desired.

Now, let  $i \in I$ . We have  $v_i = A^{n-q_i} f_n - \sum_{l=1}^{p_i} b_{il} e_{i,l+q_i}$ . First we note that  $q_i < n$  by the definition of  $U_{I,(\rho_i)}$ , so the definition of  $v_i$  makes sense. We consider the chain beginning with  $v_i - (A^{q_i+P_i} v_i \gg q_i + P_i)$ . Note that  $A^{q_i} v_i$  is just  $b$  with row  $i$  zeroed out. For brevity, we write  $b_i := A^{q_i} v_i$ . Note that  $b_i \ll P_i$  has rows  $l$  zeroed out, for all  $l$  with  $q_l < q_i$ . This ensures that shifting  $b_i \ll P_i$  right  $q_i + P_i$  times can be inverted by shifting left  $q_i + P_i$  times. That is,

$$A^{q_i+P_i} v_i = b_i \ll P_i = ((b_i \ll P_i) \gg q_i + P_i) \ll q_i + P_i = A^{q_i+P_i} (A^{q_i+P_i} v_i \gg q_i + P_i).$$

This shows that the chain has length at most  $q_i + P_i$ , as desired.  $\square$

*Proof of (2).* The sum of the lengths is

$$\sum_{i \notin I} (p_i + q_i) + (n + P) + \sum_{i \in I} (q_i + P_i).$$

Writing  $I = \{i_1 < \dots < i_{|I|}\}$ , we note that  $P = p_{i_1}$ , that  $P_{i_{|I|}} = 0$ , and that for  $l < |I|$  we have  $P_{i_l} = p_{i_{l+1}}$ . Thus, the sum above is

$$\begin{aligned} \sum_{i \notin I} (p_i + q_i) + (n + p_{i_1}) + \sum_{l=1}^{|I|} (q_{i_l} + p_{i_{l+1}}) = \\ \sum_{i \notin I} (p_i + q_i) + n + \sum_{l=1}^{|I|} (q_{i_l} + p_{i_l}) = n + \sum_i (q_i + p_i) = m + n. \end{aligned}$$

$\square$

*Proof of (3).* Let  $W$  be the span of the chains listed. We need to show that  $W = \mathbb{C}^{m+n}$ . Because every  $i \in I$  satisfies  $q_i < n$ , clearly  $\langle e_{ij} \rangle_{i,j:q_i \geq n} \subseteq W$ .

I claim that  $f_n \in W$  as well. To see this, we consider the chain beginning with  $f_n - (A^{n+P} f_n \gg n + P)$ . As explained in the proof of (1), we have  $A^{n+P} f_n \in \langle e_{ij} \rangle_{i,j:q_i \geq n}$ . Consequently,  $(A^{n+P} f_n \gg n + P) \in \langle e_{ij} \rangle_{i,j:q_i \geq n} \subseteq W$ . Because  $f_n - (A^{n+P} f_n \gg n + P) \in W$ , this implies that  $f_n \in W$ .

Because  $AW \subseteq W$  (obvious, since  $W$  is the span of chains), the fact that  $f_n \in W$  implies that  $f_i \in W$  for each  $i$ , and also  $b \ll l \in W$  for each  $l \geq 0$ .

Now we are left with showing that  $\langle e_{ij} \rangle_{i,j:q_i < n} \subseteq W$ . This is obvious for  $i \notin I$ . For  $i \in I$ , we do it inductively. Fix  $i \in I$ , and suppose we have already

shown that for all  $i' \in I$  with  $q_{i'} > q_i$ , we have  $\langle e_{ij} \rangle_{j \text{ arbitrary}} \subseteq W$ . We will show that  $\langle e_{ij} \rangle_{j \text{ arbitrary}} \subseteq W$ .

To see this, we consider the chain beginning with  $v_i - (A^{q_i+P_i}v_i \gg q_i + P_i)$ . (Recall  $v_i = A^{n-q_i}f_n - \sum_{l=1}^{p_i} b_{il}e_{i,l+q_i}$ .) Because  $AW \subseteq W$ , and  $b_{i,p_i} \neq 0$  (by definition of  $p_i$ ), it suffices to show that  $\sum_{l=1}^{p_i} b_{il}e_{i,l+q_i} \in W$ . As explained in the proof of (1), we have  $A^{q_i+P_i}v_i \in \langle e_{lj} \rangle_{q_l \geq q_i}$ . And since  $A^{q_i+P_i}v_i$  has row  $i$  zeroed out, in fact  $A^{q_i+P_i}v_i \in \langle e_{lj} \rangle_{l:l \neq i \wedge q_l \geq q_i}$ . Hence,  $A^{q_i+P_i}v_i \gg q_i + P_i \in \langle e_{lj} \rangle_{l:l \neq i \wedge q_l \geq q_i}$ . By our inductive hypothesis,  $\langle e_{lj} \rangle_{l:l \neq i \wedge q_l \geq q_i} \subseteq W$ , and consequently  $A^{q_i+P_i}v_i \gg q_i + P_i \in W$ . Since we know  $v_i - (A^{q_i+P_i}v_i \gg q_i + P_i) \in W$ , this implies that  $v_i \in W$ . Because  $A^{n-q_i}f_n \in W$ , this then implies that  $\sum_{l=1}^{p_i} b_{il}e_{i,l+q_i} \in W$ , as desired.  $\square$

We proved (1), (2), (3), so we are done.  $\square$

Let  $\mu(I, (\rho_i))$  be the shape of the Jordan basis given in the previous lemma. Let  $X_\mu$  be the Springer fiber at  $J(\mu)$ , and let  $(X_{\mu,\alpha})_{\alpha \in \text{SYT}(\mu)}$  be the irreducible components.

Given a zero-indexed list  $L = [L_0, \dots, L_{l-1}]$ , we define  $\gamma(L) = \sum_i iL_i$ . We will be interested in this thing because the dimension of  $X_\mu$  is  $\gamma([\mu_1, \dots, \mu_l])$ . Let  $s$  be the function taking integer lists to lists which sorts the input in nonincreasing order.

**Lemma 8.7.**  $\gamma([\mu_1, \dots, \mu_l]) = \gamma([0, \lambda_1, \dots, \lambda_k]) - \text{something}$ .

*Proof.* Let  $L = [q_{i_0}, \lambda_1, \dots, \lambda_k]$ . First we compute

$$\gamma(L) - \gamma(s(L)) = \sum_{i: \lambda_i \geq q_{i_0}} (\lambda_i - q_{i_0}).$$

Now, we have  $s(L) = [\dots, q_{i_0}, \dots, q_{i_1} + p_{i_1}, \dots, q_{i_2} + p_{i_2}, \dots, q_{i_r} + p_{i_r}, \dots]$ . Note that  $\mu = [\dots, q_{i_0} + p_{i_1}, \dots, q_{i_1} + p_{i_2}, \dots, \dots, q_{i_r} + p_{i_{r+1}}, \dots]$ . Let  $L'$  be like  $\mu$ , but with  $q_{i_x} + p_{i_{x+1}}$  replaced by  $q_{i_x} + p_{i_x}$ ; that is,  $L' = [\dots, q_{i_0}, \dots, q_{i_1} + p_{i_1}, \dots, q_{i_2} + p_{i_2}, \dots, q_{i_r} + p_{i_r}]$ . We compute

$$\begin{aligned} \gamma(L') - \gamma(\mu) &= \sum_{k=0}^{r-1} p_{i_{k+1}} (\#\{i \notin I : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_{k+1}} + p_{i_{k+2}}\} + 1) = \\ &= \sum_{k=0}^{r-1} \#\{i : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_{k+1}} + p_{i_{k+2}}\}. \end{aligned}$$

We compute

$$\begin{aligned}
& \gamma(s(L')) - \gamma(L') = \\
& q_{i_0} \# \{i \notin I : q_{i_k} + p_{i_1} > \lambda_i \geq q_{i_0}\} - \sum_{i \notin I : q_{i_0} + p_{i_1} > \lambda_i \geq q_{i_0}} \lambda_i + \\
& \sum_{k=0}^s \left[ q_{i_k} + p_{i_k} \# \{i \notin I : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_k} + p_{i_k}\} - \sum_{i \notin I : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_k} + p_{i_k}} \lambda_i \right] = \\
& \sum_{i \notin I : q_{i_0} + p_{i_1} > \lambda_i \geq q_{i_0}} (q_{i_0} - \lambda_i) + \sum_{k=0}^s \left[ q_{i_k} + \sum_{i \notin I : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_k} + p_{i_k}} (p_{i_k} - \lambda_i) \right] = \\
& \sum_{i : q_{i_0} + p_{i_1} > \lambda_i \geq q_{i_0}} (q_{i_0} - \lambda_i) + \sum_{k=0}^s \sum_{i \notin I : q_{i_k} + p_{i_{k+1}} > \lambda_i \geq q_{i_k} + p_{i_k}} (p_{i_k} - \lambda_i).
\end{aligned}$$

TODO: there are some errors with the above calculation.

Now,

$$\begin{aligned}
& \gamma(L) - \gamma(\mu) = \\
& [\gamma(L) - \gamma(s(L))] + [\gamma(s(L')) - \gamma(L')] + [\gamma(L') - \gamma(\mu)] = \\
& \text{something}
\end{aligned}$$

□

**Lemma 8.8.**  $U_{I,(\rho_i)} \cong B_{I,(\rho_i)} \times X_\mu$ .

*Proof.* For  $b \in B_{I,(\rho_i)}$ , let  $P_b$  be the change-of-basis matrix, with columns given by the Jordan basis of the previous lemma, so that  $J(\mu) = P_b^{-1} A_{0,b} P_b$ . From looking at the Jordan basis of the previous lemma (the basis can be expressed in terms of  $A, \lambda, e_{ij}, f_i, I, \rho_i, b$ ), it is clear that the map  $P : B_{I,(\rho_i)} \rightarrow \text{GL}_{m+n}$ , given by  $b \mapsto P_b$ , is algebraic.

Now, we remark that the Springer fiber at  $A_{0,b}$  is simply  $\{P_b U : U \in X_\mu\}$ . This gives us the isomorphism  $B_{I,(\rho_i)} \times X_\mu \rightarrow U_{I,(\rho_i)}$ .

$$(b, U) \mapsto (P_b J(\mu) P_b^{-1}, P_b U),$$

with inverse

$$(A_{0,b}, U) \mapsto (b, P_b^{-1} U).$$

□

## 8.4 Conclusion

At last we have reached the base of our recursive procedure, and we begin to propagate upwards. We write  $(X_{\mu,\alpha})_\alpha$  to denote the irreducible components of  $X_\mu$ .

**Lemma 8.9.** *The irreducible components of  $U_{I,(\rho_i)}$  are exactly the subvarieties*

$$U_{I,(\rho_i),\alpha} := \{(P_b J(\mu) P_b^{-1}, P_b U) : b \in B_{I,(\rho_i)}, U \in X_{\mu,\alpha}\}.$$

*These are distinct. There are blah of them, and each has dimension blah.*

*Proof.* We know from Corollary 8.4 that  $B_{I,(\rho_i)}$  is irreducible. So, the components of  $B_{I,(\rho_i)} \times X_\mu$  are obviously  $B_{I,(\rho_i)} \times X_{\mu,\alpha}$ . Their dimensions are blah, and there are... of them. taking image under the isomorphism gives the desired result.  $\square$

**Lemma 8.10.** *The irreducible components of  $U_0$  are exactly the  $U_{I,(\rho_i),\alpha}$ . They are distinct. There are blah of them, each of dimension blah.*

## 9 Finding the irreducible components of a springer fiber at a slodowy slice

Apply things from the previous two sections, and conclude.

## 10 A different variety

Define  $R = \{(X, \mathfrak{b}_1, \mathfrak{b}_2) : X \in \mathfrak{b}_1 \wedge u(X) \in \mathfrak{b}_2\} \subseteq \mathcal{S}'_{m,n} \times \mathcal{B}_{m+n} \times \mathcal{B}_m$ . We can obtain a subvariety of  $R$  by requiring that  $u(X)$  is in some fixed similarity class. We expect that each of these subvarieties is an irreducible component of dimension  $m^2$ . We will verify these things using our previous computations of springer fibers.

## References

- [1] N. Chriss and victor ginzburg. *Representation Theory and Complex Geometry*. Modern Birkhäuser Classics. Birkhäuser Boston, 2009.