Smoothness Characterizations and Duality of the Type II Theta Correspondence and Basic Fourier–Jacobi Models

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Overview

1. **Background and Motivation**
2. **Type II Theta Correspondence Model**
3. **Basic Fourier–Jacobi Model**
4. **Duality**

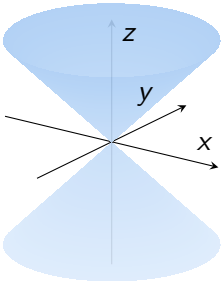
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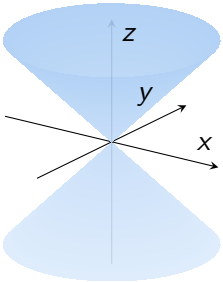
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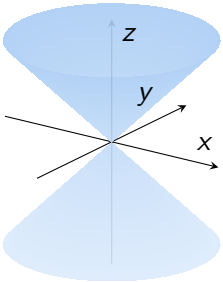


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Definition

Let X be an algebraic variety and $p \in X$. We say that p is **smooth** if the dimension of the tangent space to X at p is equal to the dimension of X. Otherwise, p is called **singular**.

Group Actions

Definition

Let G be a group and X a set. An **action** of G on X is a map

$$G \times X \longrightarrow X, \qquad (g, x) \longmapsto g \cdot x,$$

satisfying

1. $e \cdot x = x$ for all $x \in X$;
2. $(gh) \cdot x = g \cdot (h \cdot x)$ for all $g, h \in G$ and $x \in X$.

Orbits

Definition

Let G act on a variety X. The **orbit** of $x \in X$ is

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Example

Let $G = \mathrm{GL}_2(\mathbb{C}) \times \mathrm{GL}_2(\mathbb{C})$ act on $X = \mathrm{Mat}_{2\times 2}(\mathbb{C})$ by

$$(g, h) \cdot A = gAh^{-1}.$$

There are exactly three orbits, represented by

$$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \qquad \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \qquad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

Orbit Closures

Definition

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Example

Recall the action of $G = \mathrm{GL}_2(\mathbb{C}) \times \mathrm{GL}_2(\mathbb{C})$ on $\mathrm{Mat}_{2\times 2}(\mathbb{C})$. The 3 orbit closures are

$$\overline{G \cdot \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \quad \text{smooth;}$$

$$\overline{G \cdot \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}} = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : ad - bc = 0 \right\}, \quad \text{singular;}$$

$$\overline{G \cdot \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}} = \mathrm{Mat}_{2\times 2}(\mathbb{C}), \quad \text{smooth.}$$

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Example

For the action of $G = \mathrm{GL}_n(\mathbb{C}) \times \mathrm{GL}_n(\mathbb{C})$ on $\mathrm{Mat}_{n\times n}(\mathbb{C})$, the orbits are indexed by ranks $r \in \{0, \ldots, n\}$.The orbit closure indexed by r is smooth if and only if $r = 0$ or $r = n$.

Borel Subgroup

We can act by groups other than $\mathrm{GL}_n(\mathbb{C})$.

Definition

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Example

The upper triangular Borel $B_3 \subset \mathrm{GL}_3(\mathbb{C})$ is

$$B_3 = \left\{ \begin{pmatrix} a & b & c \\ 0 & d & e \\ 0 & 0 & f \end{pmatrix} \in \mathrm{GL}_3(\mathbb{C}) : a, d, f \neq 0 \right\}.$$

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Definition

A **complete flag** in $\mathbb{C}^n$ is a sequence of subspaces

$$F_1 \subset \cdots \subset F_n = \mathbb{C}^n, \qquad \dim F_i = i.$$

The **complete flag variety** $\mathrm{FL}(\mathbb{C}^n) \cong \mathrm{GL}_n(\mathbb{C})/B_n$ is the space of all complete flags in $\mathbb{C}^n$.

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- B_n acts on $\mathrm{FL}(\mathbb{C}^n)$ via matrix multiplication.
- The B_n-orbit closures in $\mathrm{FL}(\mathbb{C}^n)$ are indexed by permutations $w \in S_n$ and are known as **Schubert varieties** X_w.
- When is a Schubert variety smooth?

Pattern Avoidance and Smoothness of Schubert Varieties

Definition

A permutation w **contains** a pattern p if some subsequence of w has the same relative order as p. Otherwise, we say the permutation **avoids** the pattern.

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Theorem (Lakshmibai–Sandhya)

The Schubert variety X_w is smooth if and only if w avoids the patterns 3412 and 4231.

Motivation and Our Questions

Schubert varieties and their smoothness play an important role in:

- algebraic geometry
- algebraic combinatorics
- representation theory
- commutative algebra

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Our Questions

Can we find similar smoothness characterizations for orbit closures in

1. $B_n \times B_m$ action on $\mathrm{Mat}_{n\times m}(\mathbb{C})$?
2. B_n action on $\mathrm{FL}(\mathbb{C}^n) \times \mathbb{C}^n$?

Type II Theta Correspondence Model

Type II Theta Correspondence model refers to the $B = B_n \times B_m$ orbits in $\mathrm{Mat}_{n\times m}(\mathbb{C})$:

$$(b_n, b_m) \cdot A = b_n A b_m^{-1}.$$

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Example

A partial permutation matrix in $\mathrm{PM}(3, 3)$:

$$\sigma = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

The orbit closure $\overline{B \cdot \sigma}$ is a **matrix Schubert variety**.

Southwest Rank Table

When are matrix Schubert varieties smooth?

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Definition

For a partial permutation $\sigma \in \mathrm{PM}(m, n)$, the **southwest rank table** $\mathrm{rk}(\sigma)$ is the matrix with each entry $\mathrm{rk}(\sigma)[r, c]$ equal to the number of 1's in σ weakly southwest of the position (r, c).

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Example

Below is a partial permutation matrix and its corresponding southwest rank table:

$$\sigma = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathrm{rk}(\sigma) = \begin{pmatrix} 1 & 1 & 2 \\ 0 & 0 & 1 \end{pmatrix}.$$

Our Smoothness Characterization

Theorem (Mao–Sun–Zou, 2026)

The matrix Schubert variety $\overline{B \cdot \sigma}$ for $\sigma \in \mathrm{PM}(m, n)$ is smooth if and only if the southwest rank table of σ contains no contiguous 2×2 block of equal, nonzero entries.

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Example

Smooth

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Singular

$$\sigma' = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad \mathrm{rk}(\sigma') = \begin{pmatrix} 0 & 1 & 2 & 3 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & \mathbf{1} & \mathbf{1} \\ 0 & 0 & \mathbf{1} & \mathbf{1} \end{pmatrix}$$

Counting Smooth Matrix Schubert Varieties

The Catalan triangle:

$$
\begin{array}{ccccccccc}
1 & & & & & & & & \\
1 & 1 & & & & & & & \\
1 & 2 & 2 & & & & & & \\
1 & 3 & 5 & 5 & & & & & \\
1 & 4 & 9 & 14 & 14 & & & & \\
1 & 5 & 14 & 28 & 42 & 42 & & & \\
1 & 6 & 20 & 48 & 90 & 132 & 132 & & \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots &
\end{array}
$$

- Each entry is the sum of the entry immediately above and immediately to the left.
- Let $C(p, q)$ denote the number in row $p + 1$ and column $q + 1$.

Counting Smooth Matrix Schubert Varieties

Theorem (Mao–Sun–Zou, 2026)

For positive integers m, n and $0 \leq k \leq \min(n, m)$, the number smooth matrix Schubert varieties in $\mathrm{Mat}_{n\times m}(\mathbb{C})$ with the rank of σ being k is

$$C(n+m-k,k) = \frac{n+m-2k+1}{n+m-k+1}\binom{n+m}{k}.$$

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Example

Rank 0: $C(4,0) = 1$; rank 1: $C(3,1) = 3$; rank 2: $C(2,2) = 2$.

σ	$\begin{pmatrix}0&0\\0&0\end{pmatrix}$	$\begin{pmatrix}0&1\\0&0\end{pmatrix}$	$\begin{pmatrix}1&0\\0&0\end{pmatrix}$	$\begin{pmatrix}0&0\\0&1\end{pmatrix}$	$\begin{pmatrix}0&0\\1&0\end{pmatrix}$	$\begin{pmatrix}1&0\\0&1\end{pmatrix}$	$\begin{pmatrix}0&1\\1&0\end{pmatrix}$
$\overline{B\cdot\sigma}$	$\begin{pmatrix}0&0\\0&0\end{pmatrix}$	$\begin{pmatrix}0&*\\0&0\end{pmatrix}$	$\begin{pmatrix}*&*\\0&0\end{pmatrix}$	$\begin{pmatrix}0&*\\0&*\end{pmatrix}$	$\begin{pmatrix}*&**&*\end{pmatrix}$ det=0	$\begin{pmatrix}*&*\\0&*\end{pmatrix}$	$\begin{pmatrix}*&**&*\end{pmatrix}$

Basic Fourier–Jacobi Model

Basic Fourier–Jacobi model refers to the $B = B_n$ orbits in $\mathrm{FL}(\mathbb{C}^n) \times \mathbb{C}^n$ via matrix multiplication:

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Orbits are indexed by **colored permutations** $(w, \alpha) \in \mathrm{RB}(n)$, where $w \in S_n$ and the **antichain** $\alpha \subseteq [n]$ satisfies

$$i, j \in \alpha,\ i < j \Rightarrow w(i) > w(j).$$

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The orbit $\mathcal{O}_{(w,\alpha)}$ has representative $(w \cdot E_\bullet, v_\alpha)$, where $v_\alpha = \sum_{a \in \alpha} e_{w(a)}$.

Example

The colored permutation $(w, \alpha) = (3412, \{1, 3\})$ is visualized as 3412.

Colored Pattern Avoidance

Definition

A colored permutation (w, α) **contains** a colored pattern (p, γ) if some subsequence of w has

- the same relative order as p, and
- the same coloring as γ.

Otherwise, we say the permutation **avoids** the pattern.

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Example

The colored permutation 3142 contains the colored pattern 231 and avoids 231.

Our Smoothness Characterization

Theorem (Mao–Sun–Zou, 2026)

Let $(w, \alpha) \in \mathrm{RB}(n)$. The B-orbit closure $\overline{\mathcal{O}_{w,\alpha}}$ in $\mathrm{FL}(\mathbb{C}^n) \times \mathbb{C}^n$ is singular if and only if (w, α) satisfies at least one of the following conditions:

1. *the permutation w contains the pattern 3412, regardless of color;*
2. *the permutation w contains the pattern 4231, regardless of color;*
3. *the colored permutation (w, α) contains the pattern 321;*
4. *the colored permutation (w, α) contains the pattern 321, and this pattern is not contained in an occurrence of either 3421 or 4312.*

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Example

4312 is smooth because it contains 321 at positions $(1, 2, 3)$ as its only singular pattern, and the 321 is an occurrence of 4312.

Counting Smooth Fourier–Jacobi Orbit Closures

Let L_n denote the number of smooth Schubert varieties $X_w \subseteq \mathrm{FL}(\mathbb{C}^n)$.

- no closed formula
- $1, 1, 2, 6, 22, 88, 366, 1552, \ldots$

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Theorem (Mao–Sun–Zou, 2026)

For each n, the number of colored permutations $(w, \alpha) \in \mathrm{RB}(n)$ whose orbit closure $\overline{\mathcal{O}_{(w,\alpha)}}$ is smooth equals

$$(2n+2)\,L_n - \sum_{i=0}^{n} L_i\,L_{n-i}.$$

Duality Between the Two Models

When $m = n$, the Borel orbits in the two above cases are naturally in a bijection expected from the relative Langlands duality: $\Psi : \mathrm{PM}(n, n) \xrightarrow{\sim} \mathrm{RB}(n)$.

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Example

$$\Psi(\sigma) = 4123, \qquad \sigma = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \longleftrightarrow \quad \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix}.$$

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Smoothness is not preserved in general under the bijection between the models.

Theorem (Mao–Sun–Zou, 2026)

Let $(w, \alpha) \in \mathrm{RB}(n)$ and $\sigma = \Psi^{-1}((w, \alpha)) \in \mathrm{PM}(n, n)$. If $\overline{\mathcal{O}_{(w,\alpha)}}$ is singular for any reason other than a 4231 pattern colored as 4231, then $\overline{\mathcal{O}_\sigma}$ is singular as well.

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- the MIT PRIMES program for providing us with this wonderful opportunity to do mathematical research.
- and our families and friends for supporting us throughout this research process.

Thank You for Listening!
Any Questions?

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