Positivity in real Schubert calculus

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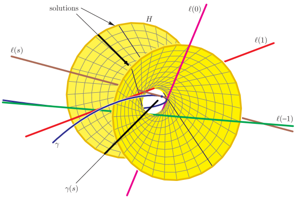

F. Sottile, “Frontiers of reality in Schubert calculus”

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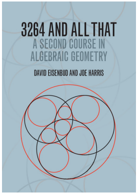
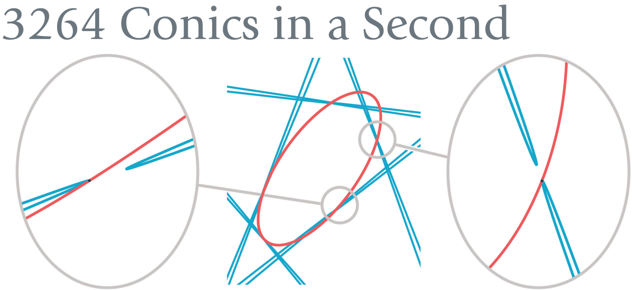
Steiner's conic problem (1848)



- How many conics are tangent to 5 given conics? ~~7776~~.
- de Jonquières (1859): 3264.
- Fulton (1984): "The question of how many solutions of real equations can be real is still very much open, particularly for enumerative problems."
- Fulton (1986); Ronga, Tognoli, Vust (1997): All 3264 conics can be real.

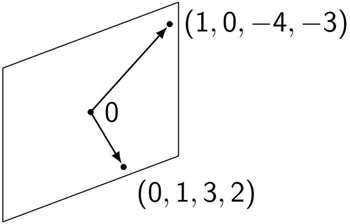


- Breiding, Sturmfels, and Timme (2020) found 5 explicit such conics.

The Grassmannian $\mathrm{Gr}_{d,m}(\mathbb{C})$

- The *Grassmannian* $\mathrm{Gr}_{d,m}(\mathbb{C})$ is the set of d-dimensional subspaces of $\mathbb{C}^m$.

$V :=$



$$= \begin{bmatrix} 1 & 0 & -4 & -3 \\ 0 & 1 & 3 & 2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & -1 & -1 \\ 0 & 2 & 6 & 4 \end{bmatrix} \in \mathrm{Gr}_{2,4}(\mathbb{C})$$

$$\Delta_{1,2} = 1, \;\; \Delta_{1,3} = 3, \;\; \Delta_{1,4} = 2, \;\; \Delta_{2,3} = 4, \;\; \Delta_{2,4} = 3, \;\; \Delta_{3,4} = 1$$

Plücker relation: $\Delta_{1,3}\Delta_{2,4} = \Delta_{1,2}\Delta_{3,4} + \Delta_{1,4}\Delta_{2,3}$

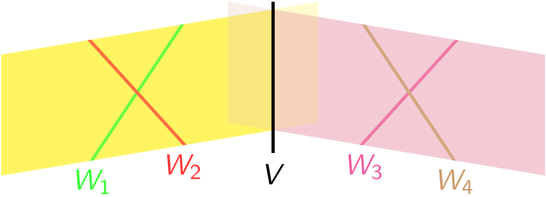
- Given $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$ as a $d \times m$ matrix, for d-subsets I of $\{1, \dots, n\}$ let $\Delta_I(V)$ be the $d \times d$ minor of V in columns I. The *Plücker coordinates* $\Delta_I(V)$ are well-defined up to a common scalar.
- $\mathrm{Gr}_{d,m}(\mathbb{C})$ is a projective variety of dimension $d(m - d)$.

Schubert calculus (1886)

- Divisor Schubert problem: given $W_1, \ldots, W_{d(m-d)} \in \mathrm{Gr}_{m-d,m}(\mathbb{C})$, find all

$$V \in \mathrm{Gr}_{d,m}(\mathbb{C}) \text{ such that } V \cap W_i \neq \{0\} \text{ for all } i.$$

- e.g. $d = 2$, $m = 4$ (projectivized). Given 4 lines $W_i \subseteq \mathbb{P}^3$, find all lines $V \subseteq \mathbb{P}^3$ intersecting all 4. Generically, there are 2 solutions.



1	2
3	4

1	3
2	4

We can see the 2 solutions explicitly when two pairs of the lines intersect.

- If the W_i's are generic, the number of solutions V is

$$\#_{d,m} := \frac{1!2!\cdots(d-1)!}{(m-d)!(m-d+1)!\cdots(m-1)!}(d(m-d))!,$$

the number of *standard Young tableaux* of rectangular shape $d \times (m-d)$.

Shapiro–Shapiro conjecture (1993)

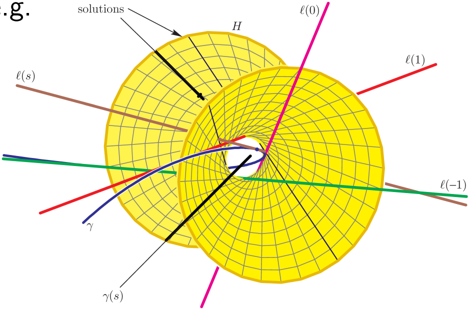
- Are there Schubert problems with all solutions real?

Shapiro–Shapiro conjecture (1993)

Let $W_1, \ldots, W_{d(m-d)} \in \mathrm{Gr}_{m-d,m}(\mathbb{R})$ osculate the moment curve $\gamma(t) := (1, t, \ldots, t^{m-1})$ at real points. Then there are $\#_{d,m}$ real solutions

$$V \in \mathrm{Gr}_{d,m}(\mathbb{R}) \text{ such that } V \cap W_i \neq \{0\} \text{ for all } i.$$

- e.g.



F. Sottile, "Frontiers of reality in Schubert calculus"

- The Schubert problem above arises in the study of linear series in algebraic geometry, differential equations, and pole placement problems in control theory.
- Bürgisser, Lerario (2020): a 'random' Schubert problem has $\approx \sqrt{\#_{d,m}}$ real solutions.

Shapiro–Shapiro conjecture (1993)

- Sottile (1999) tested the conjecture and proved it asymptotically.
- Eremenko and Gabrielov (2002) proved the conjecture for $d = 2, m - 2$.
- Mukhin, Tarasov, and Varchenko (2009) proved the full conjecture via the *Bethe ansatz*.
- Levinson and Purbhoo (2021) gave a topological proof of the conjecture.

Secant conjecture, divisor form (Sottile (2003))

Let $W_1, \ldots, W_{d(m-d)} \in \mathrm{Gr}_{m-d,m}(\mathbb{R})$ be secant to $\gamma(t) := (1, t, \ldots, t^{m-1})$ along non-overlapping intervals. Then there are $\#_{d,m}$ real solutions

$$V \in \mathrm{Gr}_{d,m}(\mathbb{R}) \textit{ such that } V \cap W_i \neq \{0\} \textit{ for all } i.$$

- The Shapiro–Shapiro conjecture is a limiting case of this conjecture.

Theorem (Karp, Purbhoo (2023))

The divisor form of the secant conjecture is true.

Total positivity

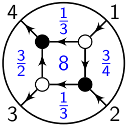
- Total positivity originated in the 1910's from orthogonal polynomials. Gantmakher and Krein (1937) showed that *totally positive matrices* (whose minors are all positive) have positive eigenvalues.

$$\begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & 4 \\ 1 & 3 & 9 \end{bmatrix} \qquad \begin{aligned} \lambda_1 &= 10.6031\cdots \\ \lambda_2 &= 1.2454\cdots \\ \lambda_3 &= 0.1514\cdots \end{aligned}$$

- Lusztig (1994) introduced total positivity for algebraic groups and flag varieties, motivated by quantum groups. An element $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$ is *totally nonnegative* if its Plücker coordinates are all nonnegative.

$$V := \begin{bmatrix} 1 & 0 & -4 & -3 \\ 0 & 1 & 3 & 2 \end{bmatrix} \in \mathrm{Gr}_{2,4}^{\geq 0}$$

$$\Delta_{1,2} = 1,\ \Delta_{1,3} = 3,\ \Delta_{1,4} = 2,\ \Delta_{2,3} = 4,\ \Delta_{2,4} = 3,\ \Delta_{3,4} = 1$$



- Postnikov (2006) parametrized $\mathrm{Gr}_{d,m}^{\geq 0}$ using *plabic graphs*.
- $\mathrm{Gr}_{d,m}^{\geq 0}$ appears in the study of cluster algebras, electrical networks, the KP hierarchy, scattering amplitudes, curve singularities, the Ising model, ...

Wronski map

- The *Wronskian* of d linearly independent functions $f_1, \ldots, f_d : \mathbb{C} \to \mathbb{C}$ is

$$\mathrm{Wr}(f_1, \ldots, f_d) := \det \begin{bmatrix} f_1 & \cdots & f_d \\ f_1' & \cdots & f_d' \\ \vdots & \ddots & \vdots \\ f_1^{(d-1)} & \cdots & f_d^{(d-1)} \end{bmatrix}.$$

- e.g. $\mathrm{Wr}(f, g) = \det \begin{bmatrix} f & g \\ f' & g' \end{bmatrix} = fg' - f'g = f^2 (\frac{g}{f})'$.
- Let $V := \langle f_1, \ldots, f_d \rangle$. Then $\mathrm{Wr}(V)$ is well-defined up to a scalar.

$$\underset{\in \mathrm{Gr}_{2,4}(\mathbb{C})}{V = \langle u^2, 1 + u^3 \rangle} \;\rightsquigarrow\; \mathrm{Wr}(V) = \det \begin{bmatrix} u^2 & 1 + u^3 \\ 2u & 3u^2 \end{bmatrix} = \underset{\in \mathbb{P}(\mathbb{C}_4[u])}{u^4 - 2u.}$$

- We identify $\mathbb{C}^m$ with the space of polynomials of degree at most $m - 1$:

$$\mathbb{C}^m \leftrightarrow \mathbb{C}_{m-1}[u], \quad (a_1, \ldots, a_m) \leftrightarrow a_1 + a_2 u + a_3 \tfrac{u^2}{2} + \cdots + a_m \tfrac{u^{m-1}}{(m-1)!}.$$

We obtain the *Wronski map* $\mathrm{Wr} : \mathrm{Gr}_{d,m}(\mathbb{C}) \to \mathbb{P}(\mathbb{C}_{d(m-d)}[u])$.

Shapiro–Shapiro conjecture and positivity conjecture

Shapiro–Shapiro conjecture (Mukhin, Tarasov, and Varchenko (2009))

Let $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$. If all complex zeros of $\mathrm{Wr}(V)$ are real, then V is real.

- e.g. If $\mathrm{Wr}(V) := (u+z_1)^2(u+z_2)^2$, the two solutions $V \in \mathrm{Gr}_{2,4}(\mathbb{C})$ are

$$\big\langle (u+z_1)(u+z_2), u(u+z_1)(u+z_2) \big\rangle \quad \text{and} \quad \big\langle (u+z_1)^3, (u+z_2)^3 \big\rangle.$$

$$= \begin{bmatrix} z_1 z_2 & z_1+z_2 & 2 & 0 \\ 0 & z_1 z_2 & 2(z_1+z_2) & 6 \end{bmatrix} \qquad = \begin{bmatrix} z_1^3 & 3z_1^2 & 6z_1 & 6 \\ z_2^3 & 3z_2^2 & 6z_2 & 6 \end{bmatrix}$$

Positivity conjecture (Mukhin, Tarasov (2017); Karp (2021))

Let $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$. If all zeros of $\mathrm{Wr}(V)$ are nonpositive, then $V \in \mathrm{Gr}_{d,m}^{\geq 0}$.

- Karp (2023): The positivity conjecture is equivalent a conjecture of Eremenko (2015), which implies the divisor form of the secant conjecture.
- Karp, Purbhoo (2023): The positivity conjecture is true.

Universal Plücker coordinates

- We want to find all $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$ with $\mathrm{Wr}(V) = (u+z_1)\cdots(u+z_n)$.
- We find the Plücker coordinates $\Delta_I(V)$ over the group algebra of $\mathfrak{S}_n$:

$$\beta_I := \sum_{\substack{X \subseteq \{1,\dots,n\}, \\ |X| = \sum I - \binom{d+1}{2}}} \sum_{\pi \in \mathfrak{S}_X} \chi^I(\pi)\pi \prod_{i \in [n] \setminus X} z_i \in \mathbb{C}[\mathfrak{S}_n],$$

where χ^I is a particular irreducible character of $\mathfrak{S}_X$.

- e.g. $\beta_{2,4} = \begin{array}{l} 2(z_1+z_2+z_3+z_4)e - z_1(2\ 3\ 4) - z_1(2\ 4\ 3) - z_2(1\ 3\ 4) \\ - z_2(1\ 4\ 3) - z_3(1\ 2\ 4) - z_3(1\ 4\ 2) - z_4(2\ 3\ 4) - z_4(2\ 4\ 3). \end{array}$

Theorem (Karp, Purbhoo (2023))

(i) The β_I's pairwise commute and satisfy the Plücker relations.

(ii) There is a bijection between the eigenspaces of the β_I's acting on $\mathbb{C}[\mathfrak{S}_n]$ and the elements $V \in \mathrm{Gr}_{d,m}(\mathbb{C})$ with $\mathrm{Wr}(V) = (u+z_1)\cdots(u+z_n)$, sending the eigenvalue of β_I to the Plücker coordinate $\Delta_I(V)$.

(iii) If $z_1, \dots, z_n \geq 0$, then the β_I's are positive semidefinite.

KP hierarchy

- The *KP equation*

$$\frac{\partial}{\partial x}\left(-4\frac{\partial u}{\partial t} + 6u\frac{\partial u}{\partial x} + \frac{\partial^3 u}{\partial x^3}\right) + 3\frac{\partial^2 u}{\partial y^2} = 0$$

models shallow water waves. It is the first equation in the *KP hierarchy*.

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- The solutions to the KP hierarchy are symmetric functions $\tau(\mathbf{x})$ in the variables $\mathbf{x} = (x_1, x_2, \dots)$ satisfying the *Hirota bilinear identity*:

$$[t^{-1}]\exp\Big(\sum_{k\geq 1}\tfrac{t^k}{k}(p_k(\mathbf{x}) - p_k(\mathbf{y}))\Big)\exp\Big(\sum_{k\geq 1} -t^{-k}\big(\tfrac{\partial}{\partial p_k(\mathbf{x})} - \tfrac{\partial}{p_k(\mathbf{y})}\big)\Big)\tau(\mathbf{x})\tau(\mathbf{y}) = 0.$$

- Sato (1981): $\tau(\mathbf{x})$ satisfies the bilinear identity if and only if its coefficients in the Schur basis $s_\lambda(\mathbf{x})$ satisfy the Plücker relations.
- A key to our proof is showing $\sum_\lambda \beta_{I_\lambda} s_\lambda(\mathbf{x})$ satisfies the bilinear identity.

Future directions

- Further explore the connection to the KP hierarchy.
- Give combinatorial proofs of the commutativity relations and Plücker relations for the β_I's.
- Find necessary and sufficient inequalities on the Plücker coordinates of V for all complex zeros of $\mathrm{Wr}(V)$ to be nonpositive. (The positivity conjecture implies that the inequalities $\Delta_I(V) \geq 0$ are necessary.)
- Address generalizations and variations of the Shapiro–Shapiro conjecture: the discriminant conjecture, the general form of the secant conjecture, the monotone conjecture, the total reality conjecture for convex curves, ...

Thank you!