

Obstructions to deforming space curves lying on complete intersection of quadrics

Hirokazu Nasu

Tokai University

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Today's slide

Plan of Talk

- 1 Hilbert schemes of Fano 3-folds
- 2 Deformation of space curves lying on a complete intersection of quadrics (an attempt to generalize known results into higher dimensional varieties)

§1 Hilbert schemes of Fano threefolds

Hilbert schemes

We work over a field $k = \bar{k}$ of **char** $k = 0$.

Let X be a projective scheme over k . We denote by **Hilb** X the Hilbert scheme of X . Today we consider the **open** and **closed** subscheme

$$\mathbf{Hilb}^{sc} X := \{\text{smooth connected curves } C \subset X\} \subset \mathbf{Hilb} X,$$

that is, the Hilbert scheme of curves in X .

Fano 3-folds

- A **Fano manifold** is a smooth projective variety X with ample $-K_X$.
- The **index** i of a Fano manifold X is the maximal integer i such that $-K_X \sim iH$ with some $H \in \text{Pic } X$.

Let X be a smooth Fano 3-fold of index i .

- $X \simeq \mathbb{P}^3$ if $i = 4$ and $X \simeq Q^3 \subset \mathbb{P}^4$ if $i = 3$, and X is called **del Pezzo** if $i = 2$, and **prime** if $i = 1$ and $\rho = 1$.
- If we restrict X with $\rho = 1$, then there exist **17** deformation equivalence classes of X (Fujita, Iskovskikh'77,'78):

i	4	3	2	1
the number of cls.	1	1	5	10
variety / cls.	\mathbb{P}^3	$Q^3 \subset \mathbb{P}^4$	del Pezzo	prime Fano

Table: the number of deformation equivalence classes of X

Hilbert scheme of Fano 3-folds

The Hilbert scheme of lines and conics have been studied widely. We can find the following survey in [Kuznetsov-Prokhorov-Shramov'18].

Theorem 1 (classical)

Let X be a smooth Fano 3-fold of $\rho = 1$ and i . Let $\Sigma(X)$ and $S(X)$ denote the Hilbert scheme of lines and conics, respectively. If X is **general** and not a **quartic double solid** ($i = d = 2$), then $\Sigma(X)$ and $S(X)$ are **generically smooth**.

i	X	$\Sigma(X)$	$S(X)$
4	\mathbb{P}^3	$\mathrm{Gr}(2, 4)$	$\mathbb{P}(\mathrm{Sym}^2 U^*)$
3	$Q = (2) \subset \mathbb{P}^4$	$\simeq \mathbb{P}^3$	$\mathrm{Bl}_{\mathrm{OG}(3,5)} \mathrm{Gr}(3, 5)$
2	$(3) \subset \mathbb{P}^4$	surface of gen.type	\mathbb{P}^2 -b'dle/surface
$(d \geq 3)$	$(2) \cap (2) \subset \mathbb{P}^5$	abelian surface	\mathbb{P}^3 -b'dle/curve
	$V_5 \subset \mathbb{P}^6$	\mathbb{P}^2	\mathbb{P}^4
1	prime (general)	smooth curve	irred. surface

$$g = 0 \text{ vs } g > 0$$

Let X be a smooth Fano 3-fold. Then

- The Hilbert scheme $\Sigma(X)$ and $S(X)$ of lines and conics on X behaves well, except for low degree case of $i = 2$ and special prime Fano.
- More generally, the Hilbert scheme of smooth rational curves on X behaves well by *vanishing of obstructions* (deformation theory).
- However, the geometry of the Hilbert scheme of curves of higher genus $g > 0$ in X becomes more complicated, due to their non-vanishings.

Infinitesimal property of Hilbert schemes

- The **tangent space** of **Hilb** X at $[C]$ is isomorphic to $H^0(N_{C/X})$.
- $C \subset X$: a locally complete intersection \implies **every obstruction** to deforming C in X is contained in $H^1(N_{C/X})$ ($\subset \text{Ext}^1(\mathcal{I}_C, \mathcal{O}_C)$) and

$$\underbrace{h^0(C, N_{C/X}) - h^1(C, N_{C/X})}_{\text{exp.dim.}(= \chi(N_{C/X}) \text{ if } C \text{ is a curve})} \leq \dim_{[C]} \text{Hilb } X \leq \underbrace{h^0(C, N_{C/X})}_{\text{tangential dimension}} .$$

- $H^1(N_{C/X}) = 0 \implies \text{Hilb } X$ is **nonsingular** at $[C]$ (Then we say C is **unobstructed** in X). The converse is not true (e.g. c.i. space curves $C \subset \mathbb{P}^3$ usually have large *obstruction spaces* but always *unobstructed*).

Question 2

Given **singular point** $[C]$, determine **the local dimension** of the Hilbert scheme **Hilb** X .

Mumford's example (pathology)

The following example appeared in a famous paper “Further pathologies in algebraic geometry [’62]”.

Example 1 (Mumford)

$\text{Hilb}^{sc} \mathbb{P}^3$ contains a generically non-reduced irreducible component W of dimension 56, whose general member C satisfies:

- 1 C is contained in a smooth cubic surface $S \subset \mathbb{P}^3$.
- 2 There exists a line E on S such that C belongs to a complete linear system $\Lambda := |-4K_S + 2E| (\simeq \mathbb{P}^{37})$ on S .

Remark 3

C is of degree 14 and genus 24, and $h^1(N_{C/\mathbb{P}^3}) = 1$ and

$$\chi(N_{C/\mathbb{P}^3}) = 56 = \dim_{[C]} \text{Hilb}^{sc} \mathbb{P}^3 < h^0(N_{C/\mathbb{P}^3}) = 57.$$

Generalization of Mumford's example

- Later **many non-reduced components** of $\mathbf{Hilb}^{sc} \mathbb{P}^3$ were found by e.g. Gruson-Peskine'82, Kleppe'87, Ellia'87, N'05, Kleppe-Ottem'15, etc. and more recently, those of $\mathbf{Hilb}^{sc} \mathbb{P}^n$ ($n > 3$) have been found by Choi-Iliev-Kim'24-1, and '24-2.
- In these examples, generic curves (of the non-reduced component) were contained in some surfaces:

	surfaces
Mumford'62, Kleppe'87, Ellia'87, N'05,23	smooth cubic in \mathbb{P}^3
Gruson-Peskine'82	non-normal cubic in \mathbb{P}^3
Kleppe-Ottem'15	smooth quartic in \mathbb{P}^3
Choi-Iliev-Kim'24-1, '24-2	ruled surface in \mathbb{P}^n

Generalization to smooth Fano 3-folds

Theorem 4 (Mumford'62,Mukai-N'09,N'10,N'19)

If X is a smooth Fano 3-fold of $\rho = 1$ and index i , then $\mathbf{Hilb}^{sc} X$ contains a **generically non-reduced** irreducible component, whose general member C is contained in the following surface $S \subset X$ and classes $[C] \in \mathbf{Pic} S$.

i	surface S	$[C] \in \mathbf{Pic} S$	E
4	del Pezzo ($S \in -\frac{i-1}{i} K_X $)	$-K_X _S + 2E$	line
3			
2			
1	$K3$ ($S \in -K_X $)	$-2K_X _S + 2E$	conic

Another generalization (with Mukai)

Theorem 5 (Mukai-N'09, char $k \geq 0$)

Let X be a smooth projective 3-fold such that

- 1 there exists a free rational curve $E \simeq \mathbb{P}^1$ on X , and
- 2 there exists a smooth surface S s.t. $E \subset S \subset X$, $E^2 = -1$ on S , and $H^1(S, N_{S/X}) = p_g(S) = 0$.

Then the Hilbert scheme $\mathbf{Hilb}^{sc} X$ has infinitely many generically non-reduced irreducible components.

Theorem 6 (Mukai-N'09)

Let C be a general genus-5 curve, X_3 a general smooth cubic 3-fold, or of Fermat type cubic 3-fold:

$$X_3^{\text{Fermat}} : x_0^3 + x_1^3 + x_2^3 + x_3^3 + x_4^3 = 0 \subset \mathbb{P}^4,$$

then $\mathbf{Hom}_8(C, X_3)$ has a generically non-reduced irreducible component of dimension 4 and $h^0(C, T_{X_3}|_C) = 5$.

§2 Deformations of space curves lying on a complete intersection of quadrics

Complete intersection of quadrics

Today we consider deformations of space curves $C \subset \mathbb{P}$ lying on a smooth surface S , when S are complete intersections

$$S_2 \subset \mathbb{P}^3, \quad S_{2,2} \subset \mathbb{P}^4, \quad S_{2,2,2} \subset \mathbb{P}^5$$

of quadrics. For each S and curves C lying on S , we consider the deformations of C in the projective space \mathbb{P} using the flag

$$C \subset S \subset \mathbb{P}.$$

Hilbert-flag scheme

A main tool of our studies is the Hilbert-flag scheme $\mathbf{HF} X$ of X , i.e.

$$\mathbf{HF} X = \{(C, S) \mid C \subset S \subset X: \text{closed subschemes}\}.$$

- The normal sheaf $N_{(C,S)/X}$ of (C, S) in X is defined by the fiber product sitting in

$$\begin{array}{ccc} N_{(C,S)/X} & \xrightarrow{\pi_2} & N_{S/X} \\ \pi_1 \downarrow & \square & \downarrow |_C \\ N_{C/X} & \xrightarrow{\pi_{C/S}} & N_{S/X}|_C, \end{array}$$

where $|_C$ is the restriction of sheaves, and $\pi_{C/S} : N_{C/X} \rightarrow N_{S/X}|_C$ is the natural projection.

- If the two embeddings $C \hookrightarrow S \hookrightarrow X$ are regular, then the tangent space and the obstruction space of $\mathbf{HF} X$ at (C, S) is $H^0(N_{(C,S)/X})$ and $H^1(N_{(C,S)/X})$, and

$$h^0(X, N_{(C,S)/X}) - h^1(X, N_{(C,S)/X}) \leq \dim_{(C,S)} \mathbf{HF} X \leq h^0(X, N_{(C,S)/X}).$$

- There exist natural projections $pr_i : \mathbf{HF} X \rightarrow \mathbf{Hilb} X$ ($i = 1, 2$) corresponding to $(C, S) \mapsto [C]$, and $(C, S) \mapsto [S]$.

Correspondingly to projections pr_i ($i = 1, 2$), if $C \hookrightarrow S \hookrightarrow X$ are regular, then there exist two natural exact sequences

$$\begin{aligned} 0 &\longrightarrow \mathcal{I}_{C/S} \otimes_S N_{S/X} \longrightarrow N_{(C,S)/X} \xrightarrow{\pi_1} N_{C/X} \longrightarrow 0, \\ 0 &\longrightarrow N_{C/S} \longrightarrow N_{(C,S)/X} \xrightarrow{\pi_2} N_{S/X} \longrightarrow 0. \end{aligned}$$

Lemma 7

The Hilbert-flag scheme $\mathbf{HF} X$ is **nonsingular** at (C, S) of **expected dimension**

$$\chi(N_{(C,S)/X}) = \chi(N_{C/S}) + \chi(N_{S/X})$$

if C is a curve and

- ① X is a **Fano 3-fold** and S is **del Pezzo**, or
- ② $X = \mathbb{P}^n$, S is **del Pezzo** (embedded into \mathbb{P}^n by $|-K_S|$).

Proof.

Suppose e.g. X is Fano a 3-fold and S is del Pezzo. Then by adjunction, $N_{S/X} \simeq -K_X|_S + K_S$ and $N_{C/S} \simeq -K_S|_C + K_C$, where $-K_X$ and $-K_S$ are ample. This implies the higher cohomology groups of $N_{S/X}$ and $N_{C/S}$ vanish, so does that of $N_{(C,S)/X}$. □

Smooth quadric surface S_2 in \mathbb{P}^3

We start from curves on smooth quadrics in \mathbb{P}^3 .

Let $S = S_2 \subset \mathbb{P}^3$. Then

$$S \simeq \mathbb{P}^1 \times \mathbb{P}^1 \quad \text{and} \quad \text{Pic } S \simeq (\text{Pic } \mathbb{P}^1)^{\oplus 2} = \mathbb{Z}^2.$$

Thus every curve C on S corresponds to *bidegree* $(a, b) \in \mathbb{Z}^2$ of C . Then C is of degree $a + b$ and genus $(a - 1)(b - 1)$.

Proposition 8 (Tannenbaum'78, Kleppe'87, etc)

Let $d > 4$ and $g \geq 0$. Let $C \subset \mathbb{P}^3$ be a smooth connected curve of degree d and genus g **contained in a smooth quadric surface**. Then the maximal irreducible family $W(a, b)$ of such curves $C \subset \mathbb{P}^3$ of bidegree (a, b) is of dimension $g + 2d + 8$, and

- 1 **Hilb** \mathbb{P}^3 is **smooth** along $W(a, b)$.
- 2 The closure $\overline{W}(a, b) \subset \text{Hilb}^{sc} \mathbb{P}^3$ becomes a **generically smooth component** if $g \geq 2d - 8$, otherwise $\overline{W}(a, b)$ is a **proper closed subset** of a component of $\text{Hilb}^{sc} \mathbb{P}^3$ of codimension $2d - 8 - g$.

Sketch of proof

Let $C \subset \mathbb{P}^3$ be contained in a smooth quadric $S = S_2 \subset \mathbb{P}^3$. Then $H^1(N_{C/S}) = 0$ and hence $\mathbf{HF} \mathbb{P}^3$ is **nonsingular** at (C, S) of expected dimension

$$\chi(N_{(C,S)}) = 2d + g + 8.$$

We see that either

$$[i] \ H^1(I_C(2)) = 0 \text{ or } [ii] \ H^1(O_C(2)) = 0$$

holds. If $H^1(I_C(2)) = 0$, then the tangent map

$$p_1 : \mathcal{T}_{\mathbf{HF} \mathbb{P}^3, (C,S)} \longrightarrow \mathcal{T}_{\mathbf{Hilb} \mathbb{P}^3, [C]}$$

of the 1st projection $pr_1 : (C', S') \mapsto [C']$ is surjective at (C, S) . Then this implies pr_1 is smooth at (C, S) .

If $H^1(O_C(2)) = 0$, then by the exact sequence

$$0 \longrightarrow N_{C/S} \longrightarrow N_{C/\mathbb{P}^3} \xrightarrow{\pi_{C/S}} N_{S/\mathbb{P}^3}|_C \simeq O_C(2) \longrightarrow 0,$$

we get $H^1(N_{C/\mathbb{P}^3}) = 0$. Thus $\mathbf{Hilb} \mathbb{P}^3$ is **nonsingular** at $[C]$. □

Smooth complete intersection $S_{2,2} \subset \mathbb{P}^4$

Let $S = S_{2,2} \subset \mathbb{P}^4$ be a smooth complete intersection. Then S is a del Pezzo surface of degree 4, isomorphic to $\mathbf{Bl}_{P_1, \dots, P_5} \mathbb{P}^2$ and $\mathbf{Pic} S \simeq \mathbb{Z}^6$ is generated by 5 exceptional curves \mathbf{e}_i ($1 \leq i \leq 5$) and the pull back of $[O_{\mathbb{P}^2}(1)]$ by $S \rightarrow \mathbb{P}^2$. Then every divisor D on S corresponds to a 7-tuple $(a; b_1, \dots, b_5)$ of integers a, b_1, \dots, b_5 by

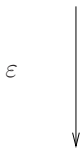
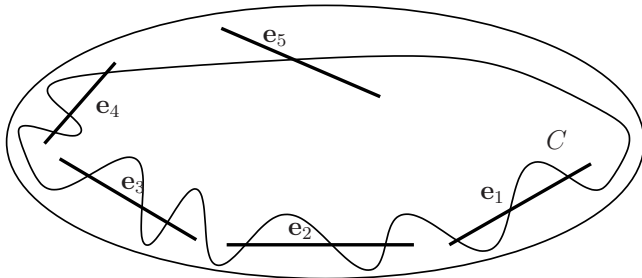
$$[D] = a\mathbf{l} - \sum_{i=1}^5 b_i \mathbf{e}_i.$$

Moreover, the coordinate $(a; b_1, \dots, b_5)$ satisfies

$$b_1 \geq \dots \geq b_5 \quad \text{and} \quad a \geq b_1 + b_2 + b_3. \quad (1)$$

Here $(a; b_1, \dots, b_5)$ is called the **standard coordinate** of $[D]$ in $\mathbf{Pic} S_{2,2}$.

Curves on $S_{2,2} \subset \mathbb{P}^4$

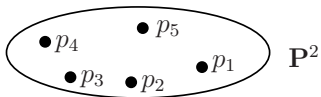


$$S_{2,2} = \text{Bl}_{p_1, \dots, p_5} \mathbb{P}^2$$

$$[C] = (9; 3, 3, 3, 3, 1) \in \text{Pic} S_{2,2} = \mathbb{Z}^6$$

$$d = 3 \cdot 9 - 3 - 3 - 3 - 3 - 1 = 14$$

$$g = \frac{(9-1)(9-2)}{2} - 3 - 3 - 3 - 3 = 16$$



Stable degeneration

Suppose that

$$C \subset S \subset \mathbb{P}$$

is a flag of a space curve C and a surface S .

Definition 2

We say C is **stably degenerate** if every small global deformation of C in \mathbb{P} is contained in a deformation of S in \mathbb{P} , i.e.,

$$C \subset S \text{ and } C \rightsquigarrow C' \implies S \rightsquigarrow \exists S' \text{ s.t. } S' \supset C'$$

Theorem 9 (Main1)

Let $C \subset S_{2,2} \subset \mathbb{P}^4$ be a smooth curve of degree $d \geq 10$ of genus $g \geq 2d - 12$, contained in a smooth c.i. $S_{2,2}$ in \mathbb{P}^4 . Let $(a; b_1, \dots, b_5)$ be the standard coordinate of $[C]$ in $\text{Pic } S_{2,2} \simeq \mathbb{Z}^6$. Then

- ① If $b_5 \geq 2$, then C is **unobstructed** and **stably degenerate**.
- ② If $b_5 = 1$ and $b_4 \geq 2$, then C is **obstructed and stably degenerate**.
- ③ If $b_5 = 0$, then C is **not stably degenerate**.

Examples

Table: curves on $S_{2,2}$ and stable degeneration

(d, g)	the class of C	the max. irred. family of C ($\subset \mathbf{Hilb}^{sc} \mathbb{P}^4$)
(14, 16)	(8; 2, 2, 2, 2, 2)	generically smooth component
(14, 16)	(9; 4, 3, 2, 2, 2)	generically smooth component
(14, 16)	(9; 3, 3, 3, 3, 1)	generically non-reduced component
(15, 18)	(9; 4, 2, 2, 2, 2)	generically smooth component
(15, 18)	(9; 3, 3, 3, 2, 1)	generically non-reduced component
⋮	⋮	⋮
(18, 24)	(9; 2, 2, 2, 2, 1)	generically non-reduced component
(18, 24)	(10; 4, 3, 3, 1, 1)	unknown ($h^1(\mathcal{I}_C(2)) = 2$)
(18, 24)	(10; 3, 3, 3, 3, 0)	a proper closed subset of a component
(18, 24)	(11; 6, 3, 2, 2, 2)	generically smooth component
⋮	⋮	⋮

Analogy of Mumford's example

Example 3

$\text{Hilb}^{sc} \mathbb{P}^4$ contains a **generically non-reduced** irreducible component W ,

- ① whose general member C is contained in a **smooth c.i.** $S = S_{2,2} \subset \mathbb{P}^4$,
- ② for general $C \in W$, there exists **a line** E on S such that

$$C \sim -3K_S + 2E$$

(Here $|C| \simeq \mathbb{P}^{29}$), and

- ③ C is of degree **14** and genus **16**.
- ④ $\dim_{[C]} \mathcal{O}_{\text{Hilb } \mathbb{P}^4} = 55$, while $h^0(C, N_{C/\mathbb{P}^4}) = 57$.

Thus $h^0(N_{C/\mathbb{P}^4}) = \dim_{[C]} \mathcal{O}_{\text{Hilb } \mathbb{P}^4} + 2$.

Smooth complete intersection $S_{2,2,2} \subset \mathbb{P}^5$

Let $S_{2,2,2} \subset \mathbb{P}^5$ be a smooth complete intersection. Then S is a **K3** surface of degree $8 = 2^3$ and genus 5. Since $N_{S/\mathbb{P}^5} \simeq \mathcal{O}_S(2)^{\oplus 2}$, we have

$$H^1(N_{S/\mathbb{P}^5}(-C)) = H^1(S, -(C - 2\mathbf{h}))^{\oplus 2},$$

where $\mathbf{h} = \mathcal{O}_S(1)$. If $C - 2\mathbf{h}$ is nef and big and $H^1(N_{(C,S)/\mathbb{P}^5}) = 0$, then C is **stably degenerate and unobstructed**. On the other hands,

Theorem 10 (Main2)

For every integer $n \geq 2$, the Hilbert scheme $\mathbf{Hilb}^{sc} \mathbb{P}^5$ contains a **generically non-reduced** components W_n ,

- 1 whose general C is contained in a $S_{2,2,2} \subset \mathbb{P}^5$,
- 2 for general $C \in W_n$, there exists **a line E** on S such that

$$C \sim n(2\mathbf{h} + E),$$

- 3 C is of degree $d = 17n$ and genus $g = 17n^2 + 1$, and
- 4 $\dim_{[C]} \mathcal{O}_{\mathbf{Hilb} \mathbb{P}^5} = g + 53$, while $h^0(N_{C/\mathbb{P}^5}) = g + 56$.

Thus $h^0(N_{C/\mathbb{P}^5}) = \dim_{[C]} \mathcal{O}_{\mathbf{Hilb} \mathbb{P}^5} + 3$. Since $\mathbf{h}.E = 1$ and $E^2 = -2$, we have $C.E = 0$ and $(C - 2\mathbf{h}).E = -2$.

Construction

We consider the family

$$W_n := \left\{ C \subset \mathbb{P}^5 \mid C \subset S \text{ for some } S = S_{2,2,2} \subset \mathbb{P}^5 \text{ and } C \sim n(2h + \mathbf{E}) \right\}$$

of curves in \mathbb{P}^5 . Then

$$\begin{array}{ccccc}
 C & \in & W^{(g+53)} & \subset & \mathbf{Hilb}^{sc} \mathbb{P}^5 \\
 \downarrow & & \downarrow \scriptstyle \mathbb{P}^g\text{-bundle} & & \\
 (\mathbf{E}, S) & \in & U^{(53)} & \subset & G \times \mathbf{Gr}(3, V) \\
 \downarrow & & \downarrow \scriptstyle \mathbf{Gr}(3, 18)\text{-bundle} & & \downarrow \\
 \mathbf{E} & \in & \mathbf{Gr}(2, 6)^{(8)} & = & \{ \text{lines in } \mathbb{P}^5 \},
 \end{array}$$

where $V = H^0(\mathbb{P}^5, \mathcal{O}_{\mathbb{P}^5}(2))$.

Key Lemma

Let X be a projective scheme, $\mathbf{HF} X$ the Hilbert-flag scheme of X , and

$$p_1 : H^0(N_{(C,S)/X}) \rightarrow H^0(N_{C/X})$$

the tangent map of the first projection $pr_1 : \mathbf{HF} X \rightarrow \mathbf{Hilb} X, (C, S) \mapsto [C]$.

Lemma 11 (Key Lemma, cf. N[23])

We have $\dim_{(C,S)} \mathbf{HF} X = \dim_{[C]} \mathbf{Hilb} X$ if

- ① $H^1(N_{(C,S)/X}) = H^0(\mathcal{I}_{C/S} \otimes_S N_{S/X}) = \mathbf{0}$, and
- ② for every $\alpha \in H^0(N_{C/X}) \setminus \text{im } p_1$, the (primary) obstruction $\text{ob}(\alpha)$ (to extend α a second order deformation over $k[t]/(t^3)$) is nonzero.

Sketch of Proof of Main2.

Let $C \subset \mathbb{P}^5$ be a smooth connected curve lying on a complete intersection $K3$ surface $S = S_{2,2,2} \subset \mathbb{P}^5$, and such that $C \sim n(2h + E)$ in $\text{Pic } S$ for $n \geq 2$, where E is a line on S .

- Since $d = 17n > 16 = 2h^2$, S is uniquely determined by C .
- Then for all $i > 0$, $H^i(N_{S/\mathbb{P}^5}(-E)) = 0$ by projective normality and $H^i(N_{E/\mathbb{P}^5}) = 0$ by ampleness. Then it follows from

$$0 \longrightarrow N_{S/\mathbb{P}^5}(-E) \longrightarrow N_{(E,S)/\mathbb{P}^5} \xrightarrow{\pi_1} N_{E/\mathbb{P}^5} \longrightarrow 0$$

that $H^i(N_{(E,S)/\mathbb{P}^5}) = 0$, which implies there exists a first order deformation of \tilde{S} of S , to which E (and hence C) does not lift.

- Then $H^i(N_{(C,S)/\mathbb{P}^5}) = 0$ for $i > 0$ and

$$H^0(N_{(C,S)/\mathbb{P}^5}) \xrightarrow{p_1} H^0(N_{C/\mathbb{P}^5}) \longrightarrow H^1(N_{S/\mathbb{P}^5}(-C)) \longrightarrow 0$$

is exact. Here p_1 is the tangent map of $pr_1 : \mathbf{HF} \mathbb{P}^5 \rightarrow \mathbf{Hilb} \mathbb{P}^5$ at (C, S) and its cokernel is of dimension 3 by

$$H^1(N_{S/\mathbb{P}^5}(-C)) \simeq H^1(O_S(2h - C))^{\oplus 3} \simeq k^3.$$

Sketch of Proof of Main2.(continued)

- We note that $H^1(N_{S/\mathbb{P}^5}(\mathbf{E} - C)) = H^1(-L^{\oplus 3}) = \mathbf{0}$, since $L = C - 2\mathbf{h} - \mathbf{E} = (n-1)(2\mathbf{h} + \mathbf{E})$ is nef and big, and we have

$$H^0(N_{S/\mathbb{P}^5}(\mathbf{E})) \xrightarrow{\text{lc}} H^0(N_{S/\mathbb{P}^5}(\mathbf{E})|_C) \longrightarrow H^1(N_{S/\mathbb{P}^5}(\mathbf{E} - C)) = \mathbf{0}.$$

- Then for every $\alpha \in H^0(N_{C/\mathbb{P}^5}) \setminus \text{im } p_1$, its *exterior component* $\pi_{C/S}(\alpha)$, i.e., the image of α in $H^0(N_{S/\mathbb{P}^5}(\mathbf{E})|_C)$, lifts to a global section β of $N_{S/\mathbb{P}^5}(\mathbf{E})$. (Here β is called an *infinitesimal deformation with poles*.)
- Applying a “modification” of the *obstructedness criterion* [Mukai-N’09] to β , we obtain $\text{ob}(\alpha) \neq \mathbf{0}$. This implies

$$\dim_{[C]} \mathbf{Hilb}^{sc} \mathbb{P}^5 = \dim_{(C,S)} \mathbf{HF} \mathbb{P}^5$$

by the key lemma. Therefore C is *obstructed* and parametrised by an *open dense subset of a component* of $\mathbf{Hilb}^{sc} \mathbb{P}^5$ (thus yields to a *non-reduced* component of $\mathbf{Hilb}^{sc} \mathbb{P}^5$). □

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Manuscripta Math., **172**(2023), 31-55.

Primary obstructions

Let X be a projective scheme over k , C a loc. c. i. closed subscheme of X , and $k[\varepsilon] := k[t]/(t^2)$ (the ring of dual numbers).

- A **first order (infinitesimal) deformation** of C is a deformation \tilde{C} ($\subset X \times \operatorname{Spec} k[\varepsilon]$) of C in X **over** $k[\varepsilon]$.
- \tilde{C} naturally corresponds to $\alpha \in H^0(C, N_{C/X}) (\simeq \operatorname{Hom}(I_C, \mathcal{O}_C))$.
- There is an element **ob**(α) in $H^1(C, N_{C/X})$ (called the **primary obstruction** of α) such that

$$\mathbf{ob}(\alpha) = 0 \iff \tilde{C} \text{ is } \mathbf{liftable} \text{ to some } \tilde{\tilde{C}} \text{ over } k[t]/(t^3).$$

- **ob**(α) can be expressed as a **cup product**, and

$$\mathbf{ob}(\alpha) = \alpha \cup \mathbf{e} \cup \alpha \quad \text{in } \operatorname{Ext}^1(I_C, \mathcal{O}_C)$$

where $\mathbf{e} := [0 \rightarrow I_C \rightarrow \mathcal{O}_X \rightarrow \mathcal{O}_C \rightarrow 0]$.

- **ob**(α) $\neq 0$ for some α implies that **Hilb** X is **singular** at $[C]$ by **infinitesimal lifting property of smoothness**.