

Obstructions to deforming space curves lying on complete intersection of quadrics

Hirokazu Nasu

Tokai University

January 26, 2026
Birational and Affine Geometry (Incheon Songdo)



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 $k = \overline{k}$ of $\text{char } k = 0$.

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 result in a survey by Kuznetsov-Prokohrov-Shramov.

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

$g = 0$ 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 $r = 2$ and special prime Fano.
- More generally, the Hilbert scheme $\mathbf{Hilb}_{d,0}^{sc} X$ of smooth rational curves on X behaves well by vanishing of obstructions (deformation theory).
- However, the geometry of the Hilbert scheme $\mathbf{Hilb}_{d,g}^{sc} X$ for higher genus $g > 0$ becomes more complicated, due to their non-vanishings.

Infinitesimal property of Hilbert schemes

- The tangent space of $\text{Hilb } X$ 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 $[C]$ (We say C is unobstructed). The converse is not true (e.g. c.i. space curves $C \subset \mathbb{P}$ usually have large obstruction spaces but always unobstructed.).

Question 2

Determine the local dimension of the Hilbert scheme at a given singular point.

Mumford's example (pathology)

The following example appeared in a famous paper “[Further pathologies in algebraic geometry \[Mumford'62\]](#)”.

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 and \mathbb{P}^3 are [innocent-looking \(a pathology\)](#).
- 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 $\text{Hilb}^{sc} \mathbb{P}^3$ were found by e.g. Gruson-Peskine'82, Kleppe'87, Ellia'87, N'05, Kleppe-Ottem'15, etc. and also those of $\text{Hilb}^{sc} \mathbb{P}^n$ ($n > 3$) have been more recently found by Choi-Iliev-Kim'24-1, and '24-2.
- In the above examples, generic curves (of the non-reduced component) were contained in the following 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 | | | |
| 3 | del Pezzo | $-K_X _S + 2E$ | line |
| 2 | $(S \in - \frac{r-1}{r} K_X)$ | | |
| 1 | $K3$ ($S \in -K_X $) | $-2K_X _S + 2E$ | conic |

Another generalization (with Mukai)

Furthermore we found out that in Mumford's example, the **(-1)-curve $E \simeq \mathbb{P}^1$ on S plays an important role.**

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

Let X be a smooth projective 3-fold satisfying the following:

- ① there exists a smooth **rational curve E** on X s.t. $N_{E/X}$ is globally generated, 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.

Remark 6

In Mumford's ex., $X = \mathbb{P}^3$, S is a **smooth cubic**, E is a **line**.

Another example (Hom scheme)

Also, an example of Hom scheme, which has a **generically non-reduced** irreducible component, was given.

Theorem 7 (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:

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

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 $\mathbf{HF} X$ the **Hilbert-flag scheme** of X , i.e.

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

If $C \hookrightarrow S \hookrightarrow X$ is regular embeddings, then

- the tang. sp. and the obst. sp. of $\mathbf{HF} X$ at (C, S) is $H^0(N_{(C,S)/X})$ and $H^1(N_{(C,S)/X})$.
- the normal sheaf $N_{(C,S)/X}$ of (C, S) in X is the fiber product sitting in

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

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

- Similarly to Hilbert schemes,

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

If $C \hookrightarrow S \hookrightarrow X$ is a sequence of regular embeddings of closed subschemes, then there exists a natural exact sequence

$$0 \longrightarrow N_{C/S} \longrightarrow N_{(C,S)/X} \xrightarrow{\pi_2} N_{S/X} \longrightarrow 0. \quad (1)$$

Lemma 8

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 Fano a 3-fold, 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, 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 and hence by (1), 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

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

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

Theorem 9 (Tannenbaum'78, Kleppe'87, etc)

Let $d > 4$ and $g \geq 0$. Let $C \subset \mathbb{P}^3$ be a smooth connected curve contained in a smooth quadric surface. Then

- ① **Hilb** \mathbb{P}^3 is nonsingular at $[C]$, and $\dim_{[C]} \mathbf{Hilb} \mathbb{P}^3 = 2d + g + 8$.
- ② The closure $\overline{W}(a, b)$ of the maximal family of such curves $C \subset \mathbb{P}^3$ of bidegree (a, b) becomes an irreducible component of $\mathbf{Hilb}^{sc} \mathbb{P}^3$ if $g \geq 2d - 8$, otherwise $\overline{W}(a, b)$ is a proper closed subset of $\mathbf{Hilb}^{sc} \mathbb{P}^3$ of codimension $2d - 8 - g$.

Sketch of proof

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

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

We see that either $H^1(\mathcal{I}_C(2)) = 0$ or $H^1(\mathcal{O}_C(2)) = 0$ holds.

If $H^1(\mathcal{I}_C(2)) = 0$, then the tangent map

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

is surjective and the 1st projection $pr_1 : (C, S) \mapsto [C]$ is smooth at (C, S) .

If $H^1(\mathcal{O}_C(2)) = 0$, then by $\mathcal{O}_C(2) \simeq N_{S/\mathbb{P}^3}|_C$ and the exact sequence

$$0 \longrightarrow N_{C/S} \longrightarrow N_{C/\mathbb{P}^3} \longrightarrow N_{S/\mathbb{P}^3}|_C \longrightarrow 0,$$

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

Smooth complete intersection $S_{2,2} \subset \mathbb{P}^3$

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 $\text{Bl}_{P_1, \dots, P_5} \mathbb{P}^2$ and $\text{Pic } S \simeq \mathbb{Z}^7$. Moreover, 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

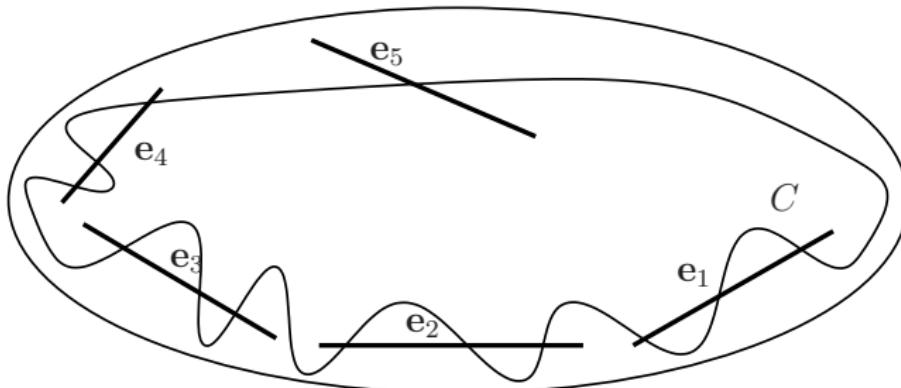
$$[D] = al - \sum_{i=1}^5 b_i \mathbf{e}_i,$$

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

$$b_1 \geq \dots \geq b_5 \quad \text{and} \quad a \geq b_1 + b_2 + b_3. \tag{2}$$

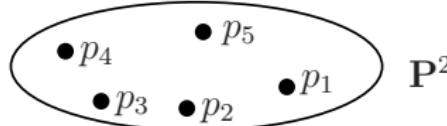
Here $(a; b_1, \dots, b_5)$ is called the **standard coordinate** of $[D]$ in $\text{Pic } S_{2,2}$.

Curves on $S_{2,2} \subset \mathbb{P}^4$ (analogy of Mumford's ex.)



$$\begin{aligned}
 S_{2,2} &= \text{Bl}_{p_1, \dots, p_5} \mathbf{P}^2 \\
 [C] &= (9; 3, 3, 3, 3, 1) \in \text{Pic} S_{2,2} = \mathbf{Z}^6 \\
 d &= 3 \cdot 9 - 3 - 3 - 3 - 3 - 1 = 14 \\
 g &= \frac{(9-1)(9-2)}{2} - 3 - 3 - 3 - 3 = 16
 \end{aligned}$$

$\downarrow \varepsilon$



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} .

Theorem 10 (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 |
| \vdots | \vdots | \vdots |
| $(18, 24)$ | $(9; 2, 2, 2, 2, 1)$ | 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 |
| \vdots | \vdots | \vdots |

Analogy of Mumford's example

Example 3

$\text{Hilb}^{sc} \mathbb{P}^4$ contains a **generically non-reduced** irreducible component W whose general member C satisfies

- ① C is contained in a **smooth c.i.** $S = S_{2,2} \subset \mathbb{P}^4$,
- ② there exists **a line E** on S such that C belongs to a complete linear system $\Lambda := |-3K_S + 2E| (\simeq \mathbb{P}^{29})$ on S , and
- ③ $\dim_{[C]} \mathcal{O}_{\text{Hilb} \mathbb{P}^4} = 55$, $h^0(C, N_{C/\mathbb{P}^4}) = 57$, and C is of degree **14** and genus **16**.

Generalized Klepppe-Ellia conjecture

Conjecture (generalized K-E conj.)

Let $C \subset S_n \subset \mathbb{P}^n$ be a smooth connected curve lying on a anti-polarized smooth del Pezzo surface $S_n \subset \mathbb{P}^n$ of degree $n \geq 3$. Then C is stably degenerate if

- ① $\chi(N_{S/\mathbb{P}^n}(-C)) \geq 0$,
- ② C is linearly normal,
- ③ $\deg(C) > 9$ for $n = 3$ and $\deg(C) > 2n$ for $n \geq 4$, and C is general in $[C] \in \text{Pic } S_n$.

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** of degree **8** (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 $\mathbf{h} = \mathcal{O}_S(1)$. Thus 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**.

Theorem 11 (Main2)

The Hilbert scheme **Hilb**^{sc} \mathbb{P}^5 contains a **generically non-reduced** components W_n ($n \geq 2$) with the following properties:

- ① every general C of W_n is a smooth connected curve contained in a smooth complete intersection **K3** surface $S_{2,2,2} \subset \mathbb{P}^5$.
- ② C is linearly equivalent to $n(2\mathbf{h} + E)$, where **E** is a line on S .
- ③ C is of degree $d = 17n$ and genus $g = 17n^2 + 1$.
- ④ $\dim_{[C]} \mathcal{O}_{\text{Hilb } \mathbb{P}^5} = g + 53$, while $h^0(N_{C/\mathbb{P}^5}) = g + 56$, thus $h^0(N_{C/\mathbb{P}^5}) = \dim_{[C]} \mathcal{O}_{\text{Hilb } \mathbb{P}^5} + 3$.

Construction

We see $h^0(\mathbb{P}^5, \mathcal{O}(2)) = \binom{5+2}{2} = 21$ and

$$h^0(\mathbb{P}^5, \mathcal{I}_E(2)) = 21 - h^0(E, \mathcal{O}_E(2)) = 18.$$

Then

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

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

Key Lemma

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

$$pr_1 : \mathbf{HF} X \rightarrow \mathbf{Hilb} X, \quad (C, S) \mapsto [C],$$

be the first projection morphism, which induces

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

Lemma 12 (Key Lemma, cf. N[’23])

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

- ① $H^1(N_{(C,S)/X}) = H^0(\mathcal{I}_{C/S} \otimes_S N_{S/X}) = 0$, and
- ② for every $\alpha \in H^0(N_{C/X}) \setminus \text{im } p_1$, the (primary) obstruction $\mathbf{ob}(\alpha)$ (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 $C \sim n(2\mathbf{h} + \mathbf{E})$ in $\text{Pic } S$ for $n \geq 2$, where \mathbf{E} is a line on S .

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

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

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

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

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

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

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

Sketch of Proof of Main2.(continued)

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

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

- 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 $H^0(N_{S/\mathbb{P}^5}(E)|_C)$, lifts to a global section β of $N_{S/\mathbb{P}^5}(E)$. (Here β is called an **infinitesimal deformation with poles**.)
- Applying a “modification” of the **obstructedness criterion** [Mukai-N’09] to β , we obtain $\text{ob}(\alpha) \neq 0$. This implies

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

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

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