



UiO : **Department of Mathematics**
University of Oslo

Join of hexagons and Calabi–Yau threefolds

Public defence

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 - Found by smoothing a certain Stanley–Reisner sphere.

I will now focus on the last point — the construction of the new Calabi–Yau’s.

Stanley–Reisner schemes

- Given a simplicial complex \mathcal{F} , we get a Stanley–Reisner scheme $\mathbb{P}(\mathcal{F})$.

Stanley–Reisner schemes

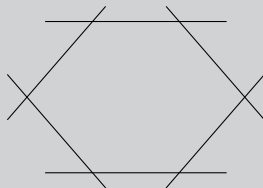
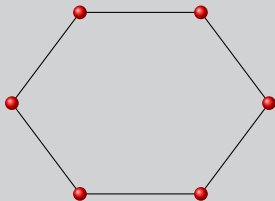
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Example

From a simplicial complex to a union of \mathbb{P}^1 's.



The ideal is generated by $x_i x_{i+2} = x_i x_{i+3} = 0$ ($i = 0, \dots, 5$).

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Smoothings of Stanley–Reisner schemes:

- Given a basis for $T^1(S_{\mathbb{P}(\mathcal{K})}/k, S_{\mathbb{P}(\mathcal{K})})_0$, we can try to find a smoothing of $X_0 = \mathbb{P}(\mathcal{K})$.

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- Given a basis for $T^1(S_{\mathbb{P}(\mathcal{K})}/k, S_{\mathbb{P}(\mathcal{K})})_0$, we can try to find a smoothing of $X_0 = \mathbb{P}(\mathcal{K})$.
- A smoothing X of X_0 will have many of the same properties:
 - The same Hilbert polynomial.
 - By semicontinuity, if X_0 is a sphere, X will be Calabi–Yau.

Calabi–Yau varieties

Definition

A **Calabi–Yau variety** is an irreducible, smooth, projective scheme X/\mathbb{C} of dimension 3 satisfying:

- $H^0(X, \mathcal{O}_X) = H^3(X, \mathcal{O}_X) = \mathbb{C}$ and $H^1(X, \mathcal{O}_X) = H^2(X, \mathcal{O}_X) = 0$.
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- Easiest invariants are the **Euler characteristic** and the **Hodge numbers**, $h^{ij} = h^j(X, \Omega_{X/\mathbb{C}}^i)$.

$$\begin{array}{ccccccc}
 & & h^{00} & & & & \\
 & h^{01} & & h^{10} & & & \\
 h^{02} & & h^{11} & & h^{20} & & \\
 h^{03} & h^{12} & & h^{21} & h^{30} & & \\
 & h^{13} & h^{22} & & h^{31} & & \\
 & & h^{23} & & h^{32} & & \\
 & & & h^{33} & & &
 \end{array}$$

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$$\begin{array}{ccccccc}
 & & & & 1 & & \\
 & & & & 0 & & 0 \\
 & & & & h^{11} & & 0 \\
 & & 0 & h^{12} & & h^{12} & 0 \\
 1 & & & & & & 1 \\
 & & 0 & h^{11} & & 0 & \\
 & & 0 & & 0 & & \\
 & & & & 1 & &
 \end{array}$$

Hodge numbers heuristic

The quintic $X = V(f) \subset \mathbb{P}^4$ is the canonical example of a Calabi–Yau. It has Hodge numbers $h^{11} = 1$ and $h^{12} = 101$.

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- The space of degree 5 polynomials $H^0(\mathbb{P}^4, \mathcal{O}_{\mathbb{P}^4}(5))$ in \mathbb{P}^4 is $\binom{4+5}{4} = \binom{9}{4} = 126$ -dimensional. Hence $\mathbb{P}(H^0(\mathbb{P}^4, \mathcal{O}_{\mathbb{P}^4}(5))) = \mathbb{P}^{125}$.

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- This is not unique, but we can act by $\mathrm{PGL}(5)$ to identify isomorphic quintics. We have $\dim \mathrm{PGL}(5) = 25 - 1 = 24$.
- In total: $125 - 24 = 101$, which is $h^{12}(X)$. ■

Mirror symmetry

- Calabi–Yau threefolds seem to “always” have “mirror partners”.

$$\begin{array}{ccccccc}
 & & & X & & & \\
 \hline
 & & & 1 & & & \\
 & & 0 & & 0 & & \\
 & 0 & & 1 & & 0 & \\
 1 & & 101 & & 101 & & 1 \\
 & 0 & & 1 & & 0 & \\
 & & 0 & & 0 & & \\
 & & & 1 & & &
 \end{array}$$

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- Calabi–Yau threefolds seem to “always” have “mirror partners”.
- Mirror partner X° to X has “mirrored Hodge diamond”.

X					
		1			
	0		0		
0		1		0	
1	101		101		1
0		1		0	
	0		0		
		1			

X°					
		1			
	0		0		
0		101		0	
1	1		1		1
0		101		0	
	0		0		
		1			

Mirror symmetry

- Calabi–Yau threefolds seem to “always” have “mirror partners”.
- Mirror partner X° to X has “mirrored Hodge diamond”.
- Hence $\chi(X^\circ) = -\chi(X)$.

X					
		1			
	0		0		
	0	1		0	
1		101		101	1
	0	1		0	
	0		0		
		1			

X°					
		1			
	0		0		
	0	101		0	
1		1		1	1
	0	101		0	
	0		0		
		1			

The mirror construction Ansatz

Sometimes the following method produces a mirror manifold of a Calabi–Yau X :

- 1 Suppose X has a natural degeneration X_0 with a finite automorphism group G .
- 2 Find a family $\pi: \mathcal{X} \rightarrow S$ on which G act, and such that the general fiber X_t has only isolated singularities.
- 3 There might be a finite subgroup H of the big torus acting. A mirror candidate is then a crepant resolution of X_t/H .

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Crepant resolutions of X_t/H exists, and are mirrors.

We can use **Roan's formula** to compute the Euler characteristic:

Theorem (Roan's formula)

$$\chi(\widetilde{X_t/H}) = \frac{1}{|H|} \sum_{g,h \in H} \chi(X_t^g \cap X_t^h)$$

The cone over dP_6

- Let $dP_6 \subset \mathbb{P}^6$ be an anticanonically embedded del Pezzo surface of degree 6. Let $C(dP_6)$ be its affine cone in \mathbb{A}^7 .
- The equations are

$$\begin{vmatrix} y & x_1 & x_2 \\ x_4 & y & x_3 \\ x_5 & x_6 & y \end{vmatrix} \leq 1.$$

The origin is an isolated singularity.

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- Can also write the equations as:

$$\leq 1$$

The two smoothing components of dP_6

We can identify one component with $\mathbb{P}(\mathcal{T}_{\mathbb{P}^2}) \setminus H$, where $\mathcal{T}_{\mathbb{P}^2}$ is the tangent bundle of \mathbb{P}^2 .

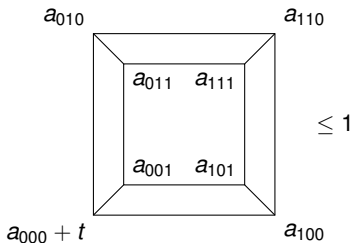
$$\begin{vmatrix} y & x_1 & x_2 \\ x_4 & y + t_1 & x_3 \\ x_5 & x_6 & y + t_2 \end{vmatrix} \leq 1$$

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We can identify one component with $\mathbb{P}(\mathcal{T}_{\mathbb{P}^2}) \setminus H$, where $\mathcal{T}_{\mathbb{P}^2}$ is the tangent bundle of \mathbb{P}^2 .

$$\begin{vmatrix} y & x_1 & x_2 \\ x_4 & y + t_1 & x_3 \\ x_5 & x_6 & y + t_2 \end{vmatrix} \leq 1$$

The second component can be identified with $(\mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1) \setminus H$, where H is a $(1, 1, 1)$ -divisor.



Construction of a new Calabi–Yau: X_1

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- Let E be a vector space with basis e_1, e_2, e_3 . Consider

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The elements are pairs of 3×3 matrices, equal up to scalar multiplication.

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- Consider the set of pairs M of matrices (A, B) with rank $1 + 1$.
- Intersect M with a generic $\mathbb{P}^{11} \subset \mathbb{P}^{17}$. Let $X_1 \triangleq M \cap \mathbb{P}^{11}$.

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Theorem

X_1 is a smooth Calabi–Yau with Euler characteristic -72 .

Construction of a new Calabi–Yau: X_2

- Let F be a vector space with basis f_1, f_2 . Consider

$$\mathbb{P}^{15} = \mathbb{P}((F \otimes F \otimes F) \oplus (F \otimes F \otimes F)).$$

The elements are pairs of $2 \times 2 \times 2$ -tensors, equal up to scalar multiplication.

- Consider the set of pairs N of tensors (A, B) with rank $1 + 1$.
- Intersect N with a generic $\mathbb{P}^{11} \subset \mathbb{P}^{15}$. Let $X_2 \triangleq N \cap \mathbb{P}^{11}$.

Theorem

X_2 is a smooth Calabi–Yau with Euler characteristic -48 .

Construction of a new Calabi–Yau: X_3

- Let E and F be as before. Consider

$$\mathbb{P}^{16} = \mathbb{P}((E \otimes E) \oplus (F \otimes F \otimes F)).$$

- Consider the set of pairs W of tensors (A, B) with rank $1 + 1$.
- Intersect W with a generic $\mathbb{P}^{11} \subset \mathbb{P}^{16}$. Let $X_3 \triangleq W \cap \mathbb{P}^{11}$.

Theorem

X_3 is a smooth Calabi–Yau with Euler characteristic -60 .

Hodge number heuristics

Conjecture

X_1 has Hodge numbers $h^{11} = 3$ and $h^{12} = 39$.

“Reason”.

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- 4 The subgroup $\{t_1 t_2 = t_3 t_4\} \subset (\mathbb{C}^*)^4 \subset \prod_{i=1}^4 \mathrm{GL}(E)$ acts trivially.
- 5 Hence $h^{12} = 72 - \left(\dim \prod_{i=1}^4 \mathrm{GL}(E) - 3 \right) = 72 - 33 = 39$. ■

Mirror candidate for X_1

Using the mirror Ansatz, we propose mirror candidates for X_1 and X_2 .

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- Choose invariant \mathbb{P}^{11} : Defined by

$$f_{ij}^\alpha = e_{ij}^\alpha + t_{-i-j}^\alpha e_{-i-j, -i-j}^{\alpha+1}$$

for $i, j \in \mathbb{Z}/3 \times \mathbb{Z}/3$ ($i \neq j$) and $\alpha = 0, 1$.

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for $i, j \in \mathbb{Z}/3 \times \mathbb{Z}/3$ ($i \neq j$) and $\alpha = 0, 1$.

- The resulting $X_{H_t} \stackrel{\Delta}{=} \mathbb{P}^{11} \cap M$ is singular with 48 isolated double point singularities.

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- We divide out by the H -action and resolve: $X_1^\circ \triangleq \widetilde{X_{H_t}}/H$.

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- We divide out by the H -action and resolve: $X_1^\circ \triangleq \widetilde{X_{H_t}}/H$.
- Roan's formula gives:

$$\chi(X_1^\circ) = \frac{1}{3} (24 + 8 \cdot 24) = 72.$$

Based on this calculation and the mirror heuristic, we conjecture:

Conjecture

X_1° is a mirror of X_1 .

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- We divide out by the H -action and resolve: $X_1^\circ \triangleq \widetilde{X_{H_t}}/H$.
- Roan's formula gives:

$$\chi(X_1^\circ) = \frac{1}{3} (24 + 8 \cdot 24) = 72.$$

Based on this calculation and the mirror heuristic, we conjecture:

Conjecture

X_1° is a mirror of X_1 .

Remark

A very similar construction gives a mirror candidate for X_2 .

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**Join of hexagons and
Calabi–Yau threefolds**
Public defence

