

DONALDSON-THOMAS INVARIANTS OF LOCAL ELLIPTIC SURFACES VIA THE TOPOLOGICAL VERTEX

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ABSTRACT. We compute the Donaldson-Thomas invariants of a local elliptic surface with section. We introduce a new computational technique which is a mixture of motivic and toric methods. This allows us to write the partition function for the invariants in terms of the topological vertex. Utilizing identities for the topological vertex (some previously known, some new), we derive product formulas for the partition functions. In the special case where the elliptic surface is a K3 surface, we get a new proof of the Katz-Klemm-Vafa formula.

1. INTRODUCTION

2. DEFINITIONS

Let $p : S \rightarrow B$ be an elliptic surface over a smooth projective curve B of genus g . We make two assumptions:

- p has a *unique* section $B \hookrightarrow S$,
- all singular fibres of π are of Kodaira type I_1 , i.e. rational nodal fibres.

We write F_x for the fibre $p^{-1}(\{x\})$, for all closed points $x \in B$. We denote the classes of the fibre and section by $B, F \in H^2(S, \mathbb{Z})$. Interesting examples are the elliptic surfaces $E(n)$, where $B = \mathbb{P}^1$ and S has $12n$ nodal fibres. Then $E(1)$ is the rational elliptic surface and $E(2)$ is the elliptic K3 surface.

Let $\beta \in H_2(S)$ be Poincaré dual to $B + dF$, where $d \geq 0$. Now let $X = \text{Tot}(K_S)$ be the total space of the canonical bundle over S . Then X is a non-compact Calabi-Yau 3-fold. Let

$$\text{Hilb}^{\beta, n}(X) = \{Z \subset X : [Z] = \beta, \chi(\mathcal{O}_Z) = n\}$$

denote the Hilbert scheme of proper subschemes $Z \subset X$ with fixed homology class and holomorphic Euler characteristics. K. Behrend associates to any \mathbb{C} -scheme of finite type Y a constructible function $\nu : Y \rightarrow \mathbb{Z}$ [?]. Applied to $\text{Hilb}^{\beta, n}(X)$, the Donaldson-Thomas invariants of X can be defined as¹

$$\text{DT}_{\beta, n}(X) := \int_{\text{Hilb}^{\beta, n}(X)} \nu \, de := \sum_{k \in \mathbb{Z}} k \, e(\nu^{-1}(\{k\})),$$

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¹If X is a compact Calabi-Yau 3-fold, R.P. Thomas's original definition of DT invariants is by the degree of the virtual cycle of $\text{Hilb}^{\beta, n}(X)$ [?]. Behrend showed that this is the same as $e(\text{Hilb}^{\beta, n}(X), \nu)$ [?]. The advantage of the definition by means of virtual cycles is that the construction works relative to a base. This implies deformation invariance of the invariants.

Drop uniqueness...
generating function
becomes product
with contribution
from multiple sec-
tions.

where $e(\cdot)$ denotes topological Euler characteristic. Many of the key properties of DT invariants are already captured by the more classical Euler characteristic version²

$$\widehat{\text{DT}}_{\beta,n}(X) := \int_{\text{Hilb}^{\beta,n}(X)} 1 \, de = e(\text{Hilb}^{\beta,n}(X)).$$

For brevity, we define

$$\begin{aligned} \text{Hilb}^{d,n}(X) &:= \text{Hilb}^{B+dF,n}(X), \\ \text{DT}_{\beta,n}(X) &:= \text{DT}_{B+dF,n}(X), \\ \widehat{\text{DT}}_{d,n}(X) &:= \text{DT}_{B+dF,n}(X). \end{aligned}$$

The generating functions of interest are

$$\begin{aligned} \text{DT}(X) &:= \sum_{d \geq 0} \text{DT}_d(X) q^d := \sum_{d \geq 0} \sum_{n \in \mathbb{Z}} \text{DT}_{d,n}(X) p^n q^d, \\ \widehat{\text{DT}}(X) &:= \sum_{d \geq 0} \widehat{\text{DT}}_d(X) q^d := \sum_{d \geq 0} \sum_{n \in \mathbb{Z}} \widehat{\text{DT}}_{d,n}(X) p^n q^d. \end{aligned}$$

Since we are dealing with generating functions and our calculations involve cut-paste methods on the moduli space, it is useful to introduce the following notation. We define

$$[\text{Hilb}^{d,\bullet}(X)] := \sum_{n \in \mathbb{Z}} [\text{Hilb}^{d,n}(X)] p^n,$$

which is an element of $K_0(\text{Var}_{\mathbb{C}}((p)))$, i.e. a Laurent series with coefficients in the Grothendieck group of varieties. We also write $\text{Hilb}^{d,\bullet}(X)$ to denote the union of all $\text{Hilb}^{d,n}(X)$. Therefore $\text{Hilb}^{d,\bullet}(X)$ is a \mathbb{C} -scheme which is locally of finite type.

3. PUSH-FORWARD TO THE SYMMETRIC PRODUCT

??

The scaling action of \mathbb{C}^* on the fibres of X lifts to the moduli space $\text{Hilb}^{d,\bullet}(X)$. Therefore

$$\int_{\text{Hilb}^{d,\bullet}(X)} 1 \, de = \int_{\text{Hilb}^{d,\bullet}(X)^{\mathbb{C}^*}} 1 \, de.$$

Recall that

$$\int_{\text{Hilb}^{d,\bullet}(X)} 1 \, de = \sum_{n \in \mathbb{Z}} p^n \int_{\text{Hilb}^{d,n}(X)} 1 \, de \in \mathbb{Z}((p)).$$

We revisit the \mathbb{C}^* -fixed point locus in detail in the next section.

Denote by $\text{Sym}^d(B)$ the d th symmetric product of B . Recall that we have projections

$$X \xrightarrow{\pi} S \xrightarrow{p} B.$$

A subscheme Z of $\text{Hilb}^{d,\bullet}(X)^{\mathbb{C}^*}$ always contains the zero section $B \subset S \subset X$. We can remove it and consider the scheme $\overline{Z} \setminus \overline{B}$. There exists a morphism

$$\begin{aligned} \rho_d : \text{Hilb}^{d,\bullet}(X)^{\mathbb{C}^*} &\longrightarrow \text{Sym}^d(B), \\ Z &\mapsto \text{supp}(p_* \pi_* \mathcal{O}_{\overline{Z} \setminus \overline{B}}), \end{aligned}$$

Can/do we want to write this easier?

²From the point of view of [?, ?], there are two natural integration maps on the semi-classical Hall-algebra. One corresponds to weighing by the Behrend function and the other to weighing by the “trivial” constructible function which is constant equal to 1.

where $\text{supp}(\cdot)$ denotes the scheme theoretic support, which is a divisor on B . We obtain

$$\int_{\text{Hilb}^{d,\bullet}(X)^{\text{c}*}} 1 \, de = \int_{\text{Sym}^d(B)} \rho_{d*}(1) \, de,$$

where $f_d := \rho_{d*}(1)$ is a constructible function on $\text{Sym}^d(B)$. Its value at a closed point $\sum_i a_i x_i$ is

$$\int_{\rho_d^{-1}(\sum_i a_i x_i)} 1 \, de.$$

We are interested in the calculation of

$$\widehat{\text{DT}}(X) = \sum_{d \geq 0} \widehat{\text{DT}}_d(X) q^d = \sum_{d \geq 0} q^d \int_{\text{Sym}^d(B)} f_d \, de.$$

We prove that the constructible function $f_d : \text{Sym}^d(B) \rightarrow \mathbb{Z}((p))$ has two multiplicative properties. The first one is described as follows. Denote by $B^{\text{sm}} \subset B$ the open subset over which the fibres F_x are smooth and by B^{sing} the N points over which the fibres F_x are singular. We can consider the restrictions of f_d to $\text{Sym}^d(B^{\text{sm}}) \subset \text{Sym}^d(B)$ and $\text{Sym}^d(B^{\text{sing}}) \subset \text{Sym}^d(B)$. Denote by $M(q)$ the MacMahon function.

Proposition 1. *Let $d_1, d_2 \geq 0$ be such that $d_1 + d_2 = d$. Then*

$$f_d(\mathbf{a} + \mathbf{b}) = \frac{(1-q)^{e(B)}}{M(q)^{e(X \setminus B)}} \cdot f_{d_1}(\mathbf{a}) \cdot f_{d_2}(\mathbf{b}),$$

for any $\mathbf{a} \in \text{Sym}^{d_1}(B^{\text{sm}})$ and $\mathbf{b} \in \text{Sym}^{d_2}(B^{\text{sing}})$.

We prove this proposition in Section 5. The following product formula is an immediate consequence of this result

$$(1) \quad \sum_{d \geq 0} q^d \int_{\text{Sym}^d(B)} f_d \, de = \frac{(1-q)^{e(B)}}{M(q)^{e(X \setminus B)}} \left(\sum_{d \geq 0} q^d \int_{\text{Sym}^d(B^{\text{sm}})} f_d \, de \right) \cdot \left(\sum_{d \geq 0} q^d \int_{\text{Sym}^d(B^{\text{sing}})} f_d \, de \right).$$

The restricted constructible functions $f_d : \text{Sym}^d(B^{\text{sm}}) \rightarrow \mathbb{Z}$ and $f_d : \text{Sym}^d(B^{\text{sing}}) \rightarrow \mathbb{Z}$ satisfy further multiplicative properties:

Proposition 2. *There exist functions $g : \mathbb{Z}_{\geq 0} \rightarrow \mathbb{Z}((p))$ and $h : \mathbb{Z}_{\geq 0} \rightarrow \mathbb{Z}((p))$, such that $g(0) = 1$, $h(0) = 1$, and*

$$f_d(\mathbf{a}) = \frac{M(q)^{e(X \setminus B)}}{(1-q)^{e(B)}} \cdot \prod_i g(a_i),$$

$$f_d(\mathbf{b}) = \frac{M(q)^{e(X \setminus B)}}{(1-q)^{e(B)}} \cdot \prod_j h(b_j),$$

for all $\mathbf{a} = \sum_i a_i x_i \in \text{Sym}^d(B^{\text{sm}})$ and $\mathbf{b} = \sum_j b_j y_j \in \text{Sym}^d(B^{\text{sing}})$.

We prove this proposition in ???. Together with Lemma 9 from the appendix, Proposition 2 and (1) gives

$$\sum_{d \geq 0} q^d \int_{\text{Sym}^d(B)} f_d \, de = \frac{M(q)^{e(X \setminus B)}}{(1-q)^{e(B)}} \cdot \left(\sum_{a=0}^{\infty} g(a) q^a \right)^{e(B)-N} \cdot \left(\sum_{b=0}^{\infty} h(b) q^b \right)^N.$$

Incorporate lemma appendix in main text?

We want to prove Lemmas 1, 2 and find formulae for $g(a)$, $h(b)$. This requires a better understanding of the strata

$$\rho_d^{-1}(\mathfrak{a} + \mathfrak{b}) \subset \mathrm{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*},$$

for all $\mathfrak{a} = \sum_i a_i x_i \in \mathrm{Sym}^{d_1}(B^{\mathrm{sm}})$ and $\mathfrak{b} = \sum_j b_j y_j \in \mathrm{Sym}^{d_2}(B^{\mathrm{sing}})$ with $d_1 + d_2 = d$. We start with a more careful study of the \mathbb{C}^* -fixed locus.

4. THE \mathbb{C}^* -FIXED LOCUS

As we already noted, the scaling action of \mathbb{C}^* on the fibres of X lifts to the moduli space $\mathrm{Hilb}^{d, \bullet}(X)$. Therefore, we only need to restrict attention to $\mathrm{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*}$.

Using the map $\pi : X \rightarrow S$, a quasi-coherent sheaf on X can be viewed as a quasi-coherent sheaf \mathcal{F} on S together with a morphism $\mathcal{F} \otimes K_S^{-1} \rightarrow \mathcal{F}$. A \mathbb{C}^* -equivariant structure on \mathcal{F} translates into a \mathbb{Z} -grading

$$\pi_* \mathcal{F} = \bigoplus_{k \in \mathbb{Z}} \mathcal{F}_k,$$

such that $\mathcal{F} \otimes K_S^{-1} \rightarrow \mathcal{F}$ is graded, i.e.

$$\mathcal{F}_k \otimes K_S^{-1} \longrightarrow \mathcal{F}_{k-1}.$$

The structure sheaf \mathcal{O}_X corresponds to

$$\pi_* \mathcal{O}_X = \bigoplus_{k=0}^{\infty} K_S^{-k}.$$

Therefore a \mathbb{C}^* -fixed morphism $\mathcal{F} \rightarrow \mathcal{O}_X$ corresponds to a graded sheaf \mathcal{F} as above together with maps

$$\begin{array}{ccccccc} \cdots & \mathcal{F}_1 & \oplus & \mathcal{F}_0 & \oplus & \mathcal{F}_{-1} & \oplus & \mathcal{F}_{-2} & \cdots \\ & & & \downarrow & & \downarrow & & \downarrow & \\ & & & \mathcal{O}_S & \oplus & K_S^{-1} & \oplus & K_S^{-2} & \cdots \end{array}$$

It is useful to re-define $\mathcal{G}_k := \mathcal{F}_{-k} \otimes K_S^k$. Then the data of a \mathbb{C}^* -fixed morphism $\mathcal{F} \rightarrow \mathcal{O}_X$ is equivalent to the following data:

- coherent sheaves $\{\mathcal{G}_k\}_{k \in \mathbb{Z}}$ on S ,
- morphisms $\{\mathcal{G}_k \rightarrow \mathcal{G}_{k+1}\}_{k \in \mathbb{Z}}$,
- morphisms $\mathcal{G}_k \rightarrow \mathcal{O}_S$ such that the following diagram commutes:

$$\begin{array}{ccccccc} \cdots & \mathcal{G}_{-1} & \longrightarrow & \mathcal{G}_0 & \longrightarrow & \mathcal{G}_1 & \longrightarrow & \mathcal{G}_2 & \longrightarrow & \cdots \\ & & & \downarrow & & \downarrow & & \downarrow & & \\ & & & \mathcal{O}_S & \xlongequal{\quad} & \mathcal{O}_S & \xlongequal{\quad} & \mathcal{O}_S & \xlongequal{\quad} & \cdots \end{array}$$

In the case of interest to us $\mathcal{G} \rightarrow \mathcal{O}_X$ is an ideal sheaf $I_Z \hookrightarrow \mathcal{O}_X$ cutting out $Z \subset X$. In the above language, this means $\mathcal{G}_k = 0$ for $k < 0$, the morphisms $\mathcal{G}_k \rightarrow \mathcal{O}_S$ are injective (hence $\mathcal{G}_k = I_{Z_k}$ is an ideal sheaf cutting out $Z_k \subset S$), and the morphisms $\mathcal{G}_k \rightarrow \mathcal{G}_{k+1}$ are injective (hence $I_{Z_k} \subset I_{Z_{k+1}}$, i.e. $Z_k \supset Z_{k+1}$). We conclude:

Proposition 3. *A closed point Z of $\mathrm{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*}$ corresponds to a finite nesting of closed subschemes of S*

$$Z_0 \supset Z_1 \supset \cdots \supset Z_l,$$

for some $l \geq 0$, such such that

$$\sum_{k=0}^l [Z_k] = B + dF \in H_2(S).$$

In the above proposition, each Z_k contains a maximal Cohen-Macaulay subcurve D_k such that $Z_k \setminus D_k$ is 0-dimensional. For $k = 0$, D_0 is the scheme-theoretic union of the section B and thickenings of certain distinct fibres F_{x_1}, \dots, F_{x_n} . Denoting the orders of thickenings by $\lambda_1^{(1)}, \dots, \lambda_1^{(n)} > 0$, we obtain³

$$D_0 = B \cup \lambda_0^{(1)} F_{x_1} \cup \dots \cup \lambda_0^{(n)} F_{x_n}.$$

This statement follows from Corollary 12 of the appendix. Next, for all $i = 1, \dots, n$ and $k \geq 1$, there are $\lambda_k^{(i)} \leq \lambda_{k-1}^{(i)}$ such that

$$D_k = \lambda_k^{(1)} F_{x_1} \cup \dots \cup \lambda_k^{(n)} F_{x_n}.$$

We conclude:

Proposition 4. *To each closed point Z of $\text{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*}$ correspond distinct closed points $x_1, \dots, x_n \in B$ for some n and (finite) 2D partitions $\lambda^{(1)}, \dots, \lambda^{(n)}$ such that*

$$\sum_{i=1}^n |\lambda^{(i)}| = d.$$

The maximal Cohen-Macaulay subcurve of Z is given by the scheme-theoretic union of the zero section B and the schemes with ideal sheaves

$$(2) \quad \bigoplus_{k=0}^{\infty} \mathcal{O}_S(-\lambda_k^{(i)} F_{x_i}) \otimes K_S^{-k},$$

for all $i = 1, \dots, n$.

In the previous section, we considered the stratum

$$\rho_d^{-1}(\mathfrak{a} + \mathfrak{b}) \subset \text{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*},$$

for any $\mathfrak{a} = \sum_{i=1}^m a_i x_i \in \text{Sym}^{d_1}(B^{\text{sm}})$ and $\mathfrak{b} = \sum_{j=1}^n b_j y_j \in \text{Sym}^{d_2}(B^{\text{sing}})$ satisfying $d_1 + d_2 = d$. By the previous lemma, it has a further stratification into locally closed subsets

$$(3) \quad \prod_{\substack{\lambda^{(1)} \vdash a_1 \\ \vdots \\ \lambda^{(m)} \vdash a_m}} \prod_{\substack{\mu^{(1)} \vdash b_1 \\ \vdots \\ \mu^{(n)} \vdash b_n}} \Sigma(x_1, \dots, x_m, y_1, \dots, y_n, \lambda^{(1)}, \dots, \lambda^{(m)}, \mu^{(1)}, \dots, \mu^{(n)}).$$

We abbreviate a stratum on the RHS by $\Sigma(x; y; \lambda; \mu)$. It should be viewed as the stratum of $Z \in \text{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*}$ for which the maximal CM subcurve $C \subset Z$ has been fixed by the data x, y, λ, μ . We are after the Euler characteristics of these strata. We will see this Euler characteristic does *not* depend on the exact location of the points x_i and y_j , but only on their number m and n and the partitions $\lambda^{(i)}$ and $\mu^{(j)}$.

³For any reduced curve C on a surface S with ideal sheaf $I_C \subset \mathcal{O}_S$ and $d > 0$, we denote by dC the scheme defined by the ideal sheaf $I_C^d \subset \mathcal{O}_S$.

5. RESTRICTION TO FORMAL NEIGHBOURHOODS

In the previous two sections, we reduced our consideration to the stratum $\Sigma(x; y; \lambda; \mu)$ of $Z \in \text{Hilb}^{d, \bullet}(X)^{\mathbb{C}^*}$ for which the maximal CM subcurve $C \subset Z$ is fixed by the data x, y, λ, μ . In this section, we further break down this stratum by cutting it up in pieces covered by formal neighbourhoods. For notational simplicity, we first consider the case where the base point is

$$ax + by \in \text{Sym}^2(B),$$

where $x \in B^{\text{sm}}$ and $y \in B^{\text{sing}}$ and compute the Euler characteristic of $\Sigma(x, y, \lambda, \mu)$. Once this is established, it is not hard to calculate the Euler characteristic of any stratum $\Sigma(x; y; \lambda; \mu)$. This leads to a proof of Propositions 1, 2, and a geometric characterization of the functions $g(a), h(b)$ of Section ??.

5.1. Fpqc cover. The idea is to use an appropriate cover of X and calculate on pieces of the cover. We first give a complex analytic definition of the cover to aid the intuition and then give the actual “algebraic-geometric cover”:

- The reduced support $B \cup F_x \cup F_y$ has three singular points: x, y, F_y^{sing} . We take small balls U_1, U_2, U_3 around these points.
- Consider the punctured space $X \setminus \{x, y, F_y^{\text{sing}}\}$ and the following three disjoint closed curves in it $B \setminus \{x, y\}, F_x \setminus \{x\}, F_y \setminus \{y, F_y^{\text{sing}}\}$. We take small tubular neighbourhoods V_1, V_2, V_3 of each of these curves. Note how the U_i and V_i together cover the reduced support $B \cup F_x \cup F_y$.
- Finally we take $W = X \setminus (B \cup F_x \cup F_y)$.

In order to work in algebraic geometry, we take U_1 to be the formal neighbourhood of $\{x\}$ in X . If R is the local ring at x , then we mean by U_1 the actual (non-noetherian) scheme

$$\text{Spec}(\varprojlim R/\mathfrak{m}^n)$$

and *not* the formal scheme $\text{Spf}(\varprojlim R/\mathfrak{m}^n)$. Similarly, we take U_2 to be the formal neighbourhood of $\{y\}$ on X and U_3 the formal neighbourhood of F_y^{sing} in X . Note that as formal schemes

$$U_i \cong \text{Spec}(\mathbb{C}[[x_1, x_2, x_3]]).$$

The point of taking spec is that the maps $U_i \rightarrow X$ is an fpqc morphism [?]. Flatness follows from the fact that localization and formal completion are flat operations [?, Cor. 3.6, Prop. 10.12, Prop. 10.13].

Next, in the punctured space $X \setminus \{x, y, F_y^{\text{sing}}\}$, we take V_1 to be the formal neighbourhood of $B \setminus \{x, y\}$. Similarly, we take V_2 to be the formal neighbourhood of $F_x \setminus \{x\}$ in $X \setminus \{x, y, F_y^{\text{sing}}\}$ and V_3 the formal neighbourhood of $F_y \setminus \{x, F_y^{\text{sing}}\}$ in $X \setminus \{x, y, F_y^{\text{sing}}\}$. Again, formal neighbourhoods are meant in the sense of taking spec of of inverse limits as above. Finally, $W = X \setminus (B \cup F_x \cup F_y)$. Now

$$\mathcal{U} = \{U_1 \rightarrow X, U_2 \rightarrow X, U_3 \rightarrow X, V_1 \rightarrow X, V_2 \rightarrow X, V_3 \rightarrow X, W \subset X\}$$

forms an fpqc cover of X . This means the data of a coherent sheaf on X is equivalent to the data of coherent sheaves on each of the open of \mathcal{U} together gluing isomorphisms on overlaps. Technically: quasi-coherent sheaves on X form a stack with respect to the fpqc topology [?, Thm. 4.23].

5.2. Local moduli spaces. We now introduce moduli spaces of closed subschemes of dimension ≤ 1 on each of the pieces of the cover \mathfrak{U} . Consider $U_1 \cong \text{Spec}(\mathbb{C}[[x_1, x_2, x_3]])$ and assume the coordinates are chosen such that $x_2 = x_3 = 0$ corresponds to the intersection of $U_1 \times_X B$ and $x_1 = x_3 = 0$ corresponds to $U_1 \times_X F_x$. Define

$$\text{Hilb}^{(1,d),n}(U_1) = \{I_Z \subset \mathcal{O}_{U_1} : [Z] = [U_1 \times_X B] + d[U_1 \times_X F_x] \text{ and } h^0(I_{Z_{CM}}/I_Z) = n\}.$$

Here the equation

$$[Z] = [U_1 \times_X B] + d[U_1 \times_X F_x]$$

means Z is supported along $(U_1 \times_X B) \cup (U_1 \times_X F_x)$ with multiplicity 1 along $(U_1 \times_X B)$ and multiplicity d along $(U_1 \times_X F_x)$. Furthermore, Z_{CM} denotes the maximal Cohen-Macaulay subcurve of Z which fits in a short exact sequence

$$0 \longrightarrow I_Z \longrightarrow I_{Z_{CM}} \longrightarrow Q \longrightarrow 0,$$

where Q is a 0-dimensional scheme. The Hilbert scheme $\text{Hilb}^{(1,d),n}(U_2)$ is defined likewise replacing the point x by y . Recall that x, y are intersections of B with the fibres F_x, F_y . For the point F_y^{sing} and its formal neighbourhood U_3 we define

$$\text{Hilb}^{d,n}(U_3) = \{I_Z \subset \mathcal{O}_{U_3} : [Z] = d[U_3 \times_X F_y] \text{ and } h^0(I_{Z_{CM}}/I_Z) = n\}.$$

Each U_i has an action of \mathbb{C}^* compatible with the fibre scaling on X and this action lifts to the moduli space. Moreover, since $U_i \cong \text{Spec}(\mathbb{C}[[x_1, x_2, x_3]])$ the bigger torus \mathbb{C}^{*3} acts on U_i and lifts to the moduli space. The existence of these “extra actions” are one of the main tricks in our paper and will be used in Section ??.

Next consider V_1 , the formal neighbourhood of the punctured zero section $B \subset X$. Define

$$\text{Hilb}^{1,n}(V_1) = \{I_Z \subset \mathcal{O}_{V_1} : [Z] = [V_1 \times_X B] \text{ and } h^0(I_{Z_{CM}}/I_Z) = n\}.$$

For V_2, V_3 we define

$$\text{Hilb}^{d,n}(V_i) = \{I_Z \subset \mathcal{O}_{V_i} : [Z] = d[V_i \times_X B] \text{ and } h^0(I_{Z_{CM}}/I_Z) = n\}.$$

Finally, for W we define

$$\text{Hilb}^{0,n}(W) = \{I_Z \subset \mathcal{O}_{V_1} : \dim(Z) = 0 \text{ and } h^0(\mathcal{O}_Z) = n\}.$$

Each V_i, W also has an action of \mathbb{C}^* compatible with the fibre scaling on X . These actions lift to the moduli space. However, *unlike* the U_i , no additional tori act on V_i, W .

As before, we use the notation $\text{Hilb}^{(1,d),\bullet}(U_1)$ for the union of all $\text{Hilb}^{(1,d),n}(U_1)$ (and similar for all other moduli spaces of this section). Like in Section 4, the components of the \mathbb{C}^* -fixed locus of $\text{Hilb}^{(1,d),\bullet}(U_1)$ are indexed by partitions $\lambda \vdash d$

$$\text{Hilb}^{(1,d),\bullet}(U_1)^{\mathbb{C}^*} = \coprod_{\lambda \vdash d} \text{Hilb}^{(1,d),\bullet}(U_1)_{\lambda}^{\mathbb{C}^*}.$$

Proposition 5. *Consider the stratum $\Sigma(x, y, a, b)$, where $a = |\lambda|$ and $b = |\mu|$. Restriction from X to the open subsets of the cover \mathfrak{U} induces a morphism*

$$\begin{aligned} \Sigma(x, y, \lambda, \mu) &\longrightarrow \text{Hilb}^{(1,a),\bullet}(U_1)_{\lambda}^{\mathbb{C}^*} \times \text{Hilb}^{(1,b),\bullet}(U_2)_{\mu}^{\mathbb{C}^*} \times \text{Hilb}^{b,\bullet}(U_3)_{\mu}^{\mathbb{C}^*} \times \\ (4) \quad &\text{Hilb}^{1,\bullet}(V_1)_{\lambda}^{\mathbb{C}^*} \times \text{Hilb}^{a,\bullet}(V_2)_{\lambda}^{\mathbb{C}^*} \times \text{Hilb}^{b,\bullet}(V_3)_{\mu}^{\mathbb{C}^*} \times \\ &\text{Hilb}^{0,\bullet}(W)^{\mathbb{C}^*}, \end{aligned}$$

which is a bijection on closed points.

Proof. Throughout this proof, we work on closed points only.

Restriction along $U_i \rightarrow X$, $V_i \rightarrow X$, $W \subset X$ gives the map set-theoretically. For any reduced base B , restriction along $U_i \times B \rightarrow X \times B$, $V_i \times B \rightarrow X \times B$, $W \times B \subset X \times B$ gives a map between moduli functors and hence induces the above morphism.

Since \mathcal{U} is an fpqc cover, fpqc descent implies that any ideal sheaf $I_Z \subset \mathcal{O}_X$ is entirely determined by its restriction along $U_i \rightarrow X$, $V_i \rightarrow X$, $W \subset X$ proving injectivity.

Conversely, given local ideal sheaves in the image of (4), their restrictions to overlaps only depend on the underlying Cohen-Macaulay curve (and not on the embedded points). Since we chose the strata such that the underlying Cohen-Macaulay curve automatically glues, there are no further gluing conditions and fpqc descent implies the morphism is surjective. \square

Remark 6. Note that the argument of Proposition 5 is purely set-theoretic in nature and no statements about the scheme structure are made.

Proposition 5 allows us to calculate the Euler characteristic of the stratum $\Sigma(x, y, \lambda, \mu)$. Recall that $a = |\lambda|$, $b = |\mu|$ so $d = a + b$. Then by (3) and Proposition 5

$$\begin{aligned} f_d(ax + by) &= e(\rho_d^{-1}(ax + by)) = e(\text{Hilb}^{1, \bullet}(V_1)^{\mathbb{C}^*}) e(\text{Hilb}^{0, \bullet}(W)^{\mathbb{C}^*}) \times \\ &\sum_{\lambda \vdash a} \sum_{\mu \vdash b} e(\text{Hilb}^{(1, a), \bullet}(U_1)_{\lambda}^{\mathbb{C}^*}) e(\text{Hilb}^{(1, b), \bullet}(U_2)_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(U_3)_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{a, \bullet}(V_2)_{\lambda}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(V_3)_{\mu}^{\mathbb{C}^*}). \end{aligned}$$

For any smooth quasi-projective 3-fold W , J. Cheah proves ??

$$e(\text{Hilb}^{\bullet}(X)) = M(p)^{e(X)},$$

where $\text{Hilb}^n(X)$ denotes the Hilbert schemes of n points on X . Moreover, for any smooth quasi-projective curve C , we have (Remark 10)

$$e(\text{Hilb}^{\bullet}(C)) = \frac{1}{(1 - q)^{e(C)}},$$

where $\text{Hilb}^n(C)$ denotes the Hilbert schemes of n points on C . Rewriting gives

$$\begin{aligned} f_d(ax + by) &= \frac{M(q)^{e(X \setminus B)}}{(1 - q)^{e(B)}} \left((1 - q) M(q) \sum_{\lambda \vdash a} e(\text{Hilb}^{(1, a), \bullet}(U_1)_{\lambda}^{\mathbb{C}^*}) e(\text{Hilb}^{a, \bullet}(V_2)_{\lambda}^{\mathbb{C}^*}) \right) \times \\ &\left((1 - q) \sum_{\mu \vdash b} e(\text{Hilb}^{(1, b), \bullet}(U_2)_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(U_3)_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(V_3)_{\mu}^{\mathbb{C}^*}) \right). \end{aligned}$$

5.3. Geometric characterization of $g(a)$ and $h(b)$. The arguments of the preceding two sections are immediately modified to any stratum $\Sigma(x; y; \lambda; \mu)$. Let U be the formal neighbourhood of any point on $B \subset S \subset X$ and define $\text{Hilb}^{(1, a), \bullet}(U)$ as in Section 5.2. Let U' be the formal neighbourhood of the singular point of any singular fibre $F \subset S \subset X$ and define $\text{Hilb}^{b, \bullet}(U')$ as in Section 5.2. Let V be the formal neighbourhood of any smooth fibre $F \setminus B$ in $X \setminus B$ and define $\text{Hilb}^{a, \bullet}(V)$ as in Section 5.2. Let V' be the formal neighbourhood of any singular fibre $F \setminus (B \cup F^{\text{sing}})$ in $X \setminus (B \setminus F^{\text{sing}})$ and define $\text{Hilb}^{b, \bullet}(V')$ as in Section 5.2.

Proposition 7. For any $a, b > 0$ define

$$\begin{aligned} g(a) &:= (1 - p) M(p) \sum_{\lambda \vdash a} e(\text{Hilb}^{(1, a), \bullet}(U)_{\lambda}^{\mathbb{C}^*}) e(\text{Hilb}^{a, \bullet}(V)_{\lambda}^{\mathbb{C}^*}) \in \mathbb{Z}[p], \\ (5) \quad h(b) &:= (1 - p) \sum_{\mu \vdash b} e(\text{Hilb}^{(1, b), \bullet}(U)_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(U')_{\mu}^{\mathbb{C}^*}) e(\text{Hilb}^{b, \bullet}(V')_{\mu}^{\mathbb{C}^*}) \in \mathbb{Z}[p], \end{aligned}$$

and let $g(0) := 1$, $h(0) := 1$. Then

$$f_d(\mathbf{a} + \mathbf{b}) = \frac{M(q)^{e(X \setminus B)}}{(1-q)^{e(B)}} \cdot \prod_i g(a_i) \cdot \prod_j h(b_j),$$

for any $\mathbf{a} = \sum_i a_i x_i \in \text{Sym}^d(B^{\text{sm}})$ and $\mathbf{b} = \sum_j b_j y_j \in \text{Sym}^d(B^{\text{sing}})$.

We immediately deduce:

Corollary 8. *Propositions 1, 2 are true for $g(a)$ and $h(b)$ defined by (5).*

6. REDUCTION TO THE TOPOLOGICAL VERTEX

In this section, we prove Theorem ?? of the introduction by expressing $g(a)$ and $h(b)$ in terms of the topological vertex.

APPENDIX A. ODDS AND ENDS

A.1. Weighted Euler characteristics of symmetric products. In this section we prove the following formula for the weighted Euler characteristic of symmetric products.

Lemma 9. *Let S be a scheme of finite type over \mathbb{C} and let $e(S)$ be its topological Euler characteristic. Let $g : \mathbb{Z}_{\geq 0} \rightarrow \mathbb{Z}((Q))$ be any function with $g(0) = 1$. Let $f_d : \text{Sym}^d(S) \rightarrow \mathbb{Z}((Q))$ be the constructible function defined by $f_d(\sum_i a_i x_i) = \prod_i g(a_i)$. Then*

$$\sum_{d=0}^{\infty} u^d \int_{\text{Sym}^d(S)} f_d de = \left(\sum_{a=0}^{\infty} g(a) u^a \right)^{e(S)}.$$

Remark 10. In the special case where $g = f_d \equiv 1$, the lemma recovers MacDonald's formula: $\sum_{d=1}^{\infty} e(\text{Sym}^d(S)) u^d = (1-u)^{-e(S)}$.

The lemma is essentially a consequence of the existence of a power structure on the Grothendieck group of varieties defined by symmetric products and the compatibility of the Euler characteristic homomorphism with that power structure []. For convenience's sake, we provide a direct proof here.

Proof. The d th symmetric product admits a stratification with strata labelled by partitions of d . Associated to any partition of d is a unique tuple (m_1, m_2, \dots) of non-negative integers with $\sum_{j=1}^{\infty} j m_j = d$. The stratum labelled by (m_1, m_2, \dots) parameterizes collections of points where there are m_j points of multiplicity j . The full stratification is given by:

$$\text{Sym}^d(S) = \bigsqcup_{\substack{(m_1, m_2, \dots) \\ \sum_{j=1}^{\infty} j m_j = d}} \left\{ \left(\prod_{j=1}^{\infty} S^{m_j} \right) - \Delta \right\} / \prod_{j=1}^{\infty} \sigma_{m_j}$$

where by convention, S^0 is a point, Δ is the large diagonal, and σ_m is the m th symmetric group. Note that the function f_d is constant on each stratum and has value $\prod_{j=1}^{\infty} g(j)^{m_j}$. Note also that the action of $\prod_{j=1}^{\infty} \sigma_{m_j}$ on each stratum is free.

For schemes over \mathbb{C} , topological Euler characteristic is additive under stratification and multiplicative under maps which are (topological) fibrations. Thus

$$\int_{\text{Sym}^d(S)} f_d de = \sum_{\substack{(m_1, m_2, \dots) \\ \sum_{j=1}^{\infty} j m_j = d}} \left(\prod_{j=1}^{\infty} g(j)^{m_j} \right) \frac{e(S^{\sum_j m_j} - \Delta)}{m_1! m_2! m_3! \dots}.$$

For any natural number N , the projection $S^N - \Delta \rightarrow S^{N-1} - \Delta$ has fibers of the form $S - \{N-1 \text{ points}\}$. The fibers have constant Euler characteristic given by $e(S) - (N-1)$ and consequently, $e(S^N - \Delta) = (e(S) - (N-1)) \cdot e(S^{N-1} - \Delta)$. Thus by induction, we find $e(S^N - \Delta) = e(S) \cdot (e(S) - 1) \cdots (e(S) - (N-1))$ and so

$$\frac{e(S^{\sum_j m_j} - \Delta)}{m_1! m_2! m_3! \cdots} = \binom{e(S)}{m_1, m_2, m_3, \dots}$$

where the right hand side is the generalized multinomial coefficient.

Putting it together and applying the generalized multinomial theorem, we find

$$\begin{aligned} \sum_{d=0}^{\infty} \int_{\text{Sym}^d(S)} f_d \, de &= \sum_{(m_1, m_2, \dots)} \prod_{j=1}^{\infty} (g(j)u^j)^{m_j} \binom{e(S)}{m_1, m_2, m_3, \dots} \\ &= \left(1 + \sum_{j=1}^{\infty} g(j)u^j \right)^{e(S)} \end{aligned}$$

which proves the lemma. \square

A.2. Some geometry of curves on elliptic surfaces. In this subsection we prove the following lemma and corollary, which will tell us what is the reduced support of all curves in the class $\beta = B + dF$.

Lemma 11. *For any line bundle ϵ on B , multiplication by the canonical section of $\mathcal{O}(B)$ induces an isomorphism*

$$H^0(S, \pi^*(\epsilon)(B)) \cong H^0(S, \pi^*(\epsilon)).$$

Corollary 12. *Let $\beta = B + dF \in H_2(S)$. Then the Chow variety of curves in the class β is isomorphic to $\text{Sym}^d(B)$ where a point $\sum_i d_i x_i \in \text{Sym}^d(B)$ corresponds to the curve $B + \sum_i d_i F_{x_i}$.*

Proof. The corollary follows immediately from the lemma since the Chow variety is the space of effective divisors and the lemma implies that any effective divisor in the class β is a union of the section B with an effective divisor pulled by from the base.

To prove lemma 11 we proceed as follows. For any line bundle δ on B , the Leray spectral sequence yields the short exact sequence:

$$0 \rightarrow H^0(B, \delta \otimes R^1 \pi_* \mathcal{O}) \rightarrow H^1(S, \pi^* \delta) \xrightarrow{\alpha} H^1(B, \delta) \rightarrow 0,$$

in particular, α is a surjection.

Then the long exact cohomology sequence associated to

$$0 \rightarrow \pi^* \delta \otimes \mathcal{O}(-B) \rightarrow \pi^* \delta \rightarrow \mathcal{O}_B \otimes \pi^* \delta \rightarrow 0$$

is

$$\cdots \rightarrow H^1(S, \pi^*(\delta)) \xrightarrow{\alpha} H^1(B, \delta) \rightarrow H^2(S, \pi^* \delta \otimes \mathcal{O}(-B)) \rightarrow H^2(S, \pi^* \delta) \rightarrow 0,$$

and since α is a surjection, we get an isomorphism of the last two terms. We apply Serre duality to that isomorphism and we use the fact that $K_S = \pi^*(K_B \otimes L)$ where $L = (R\pi_* \mathcal{O}_S)^\vee$ [?, prop?] to obtain

$$H^0(S, \pi^*(\delta^{-1} \otimes K_B \otimes L)(B)) \cong H^0(S, \pi^*(\delta^{-1} \otimes K_B \otimes L)).$$

Letting $\delta = K_B \otimes L \otimes \epsilon^{-1}$, the lemma is proved. \square

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