THE ASPINWALL-MORRISON CALCULATION AND GROMOV-WITTEN THEORY

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Abstract. We connect the Aspinwall-Morrison calculation to Gromov-Witten theory.

1. Introduction

I. A bit of history. (See [3] for a good reference on the history of the problem.) One of the problems in the old and recent story of mirror symmetry has been the issue of multiple covers on a Calabi-Yau 3-fold $X$. In the pre-Gromov-Witten era, this problem can be explained in terms of topological field theories.

Let $X$ be a Calabi-Yau threefold and $H_1, H_2, H_3 \in H^2(X)$. The corresponding 3-point correlator in the A-model of $X$ is a path integral that can be expressed as follows:

$$\langle H_1, H_2, H_3 \rangle = \int_X H_1 H_2 H_3 + \sum_{\beta \in H_2(X)} N_\beta(H_1, H_2, H_3) q^{\beta}.$$  

(1)

We explain the notation. The parameter $q = (q_1, ... q_k)$ is a local coordinate on the Kähler moduli space of $X$. Let $(d_1, ..., d_k)$ be the coordinates of $\beta$ with respect to an integral base of the Mori cone of $X$. Then $q^\beta := q^{d_1} \cdots q^{d_k}$.

The path integral is not a well defined notion, but beyond that, and probably more importantly, there is no rigorous definition of $N_\beta(H_1, H_2, H_3)$ in the framework of topological field theories. Let $Z_i$ for $i = 1, 2, 3$ be a cycle whose fundamental class is Poincaré dual to $H_i$. Heuristically, the "invariant" $N_\beta(H_1, H_2, H_3)$ is described as the "number" of holomorphic maps in

$$\{f : \mathbb{P}^1 \to X \mid f_*([\mathbb{P}^1]) = \beta, f(0) \in Z_1, f(1) \in Z_2, f(\infty) \in Z_3\}.$$  

(2)

This is certainly not precise, for there may be infinitely many such maps. Let $C \subset X$ be a smooth rational curve. Fix an isomorphism $g : \mathbb{P}^1 \to C$. For any degree $k$ multiple cover $f : \mathbb{P}^1 \to \mathbb{P}^1$ the composition $f \circ g : \mathbb{P}^1 \to C$ satisfies $(f \circ g)_*([\mathbb{P}^1]) = k[C]$. One would then naturally ask:

What is the contribution of the space of degree $k$ multiple covers of $C$ to the "invariant" $N_{k[C]}(H_1, H_2, H_3)$?

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Since this question is about the numbers $N_{k|C}(H_1, H_2, H_3)$, it is not a well posed one. It can be made precise in the framework of Gromov-Witten theory.

The answer was conjectured in [5] by looking at the classical example of a Calabi-Yau. If $X$ is a quintic threefold then $H^2(X)$ is one dimensional. Let $H$ be its generator. The 3-point correlator of the quintic can be calculated explicitly:

$$\langle H, H, H \rangle = 5 + \sum_{d=1}^{\infty} n_d d^3 \frac{q^d}{1 - q^d},$$

where $n_d$ is the virtual number of degree $d$ rational curves (instantons) in the quintic. The instanton number $n_d$ agrees with the number of degree $d$ rational curves in the quintic if every rational curve of degree $d$ is smooth, isolated and with normal bundle $N = O(-1) \oplus O(-1)$. This is not the case for there are 6-nodal rational plane quintic curves on a generic quintic threefold (see [12]), hence a rigorous definition of the instanton numbers $n_d$ did not exist.

The last equation can be transformed as follows:

$$\langle H, H, H \rangle = 5 + \sum_{d=1}^{\infty} \left( \sum_{k|d} n_k k^3 \right) q^d.$$

By comparing it to the equation (1) we can see that:

$$N_d(H, H, H) = \sum_{k|d} n_k k^3.$$

It looks that each degree $k$ rational curve $C$ in the quintic 3-fold $X$ contributes by:

$$\int_C H \cdot \int_C H \cdot \int_C H$$

to $N_d(H, H, H)$ for any $d$ such that $k|d$.

For a general Calabi-Yau $X$, the (pre Gromov-Witten) multiple cover formula can be formulated as follows:

Let $C \subset X$ be a smooth, rational curve such that $N_{C/X} = O_C(-1) \oplus O_C(-1)$. The contribution of degree $k$ multiple covers of $C$ in $N_{k|C}(H_1, H_2, H_3)$ is:

$$\int_C H_1 \cdot \int_C H_2 \cdot \int_C H_3.$$
It follows from the above equation that:

\[
N_\beta(H_1, H_2, H_3) = \sum_{\beta = d\gamma} n_\gamma \int_\gamma H_1 \int_\gamma H_2 \int_\gamma H_3
\]

(8)

\[
= (\sum_{\beta = d\gamma} n_\gamma d^{-3}) \int_\beta H_1 \int_\beta H_2 \int_\beta H_3
\]

where \(n_\gamma\) is the virtual number (instantons) of rational curves of type \(\gamma\) in \(X\).

A rigorous definition of \(N_\beta\) and \(n_\beta\) requires a new conceptual framework which is now known as Gromov-Witten theory. Let \(X\) be a smooth, projective manifold and \(\beta \in H_2(X)\). There is a moduli stack \(\overline{M}_{0,n}(X, \beta)\) which parametrizes pointed, stable maps of degree \(\beta\). Universal properties of these moduli stacks imply the existence of several features:

\[
e = (e_1, e_2, ..., e_n) : \overline{M}_{0,n}(X, \beta) \to X^n, \pi_n : \overline{M}_{0,n}(X, \beta) \to \overline{M}_{0,n-1}(X, \beta)
\]

(9) \(\pi : \overline{M}_{0,n}(X, \beta) \to \overline{M}_{0,0}(X, \beta), \hat{\pi} : \overline{M}_{0,n}(X, \beta) \to \overline{M}_{0,1}\).

The map \(e\) evaluates the pointed, stable map at the marked points, \(\pi_n\) forgets the last marked point and collapses the unstable components of the source curve, \(\pi\) forgets the marked points and \(\hat{\pi}\) forgets the map and stabilizes the pointed source curve. The expected dimension of \(\overline{M}_{0,n}(X, \beta)\) is \(\dim X + \int_\beta (-K_X) + n - 3\). The dimension of the moduli stack of stable maps may be greater than the expected dimension. In this case, a Chow class of the expected dimension has been constructed. It plays the role of the fundamental class, hence it is called the virtual fundamental class and denoted by \(\overline{M}_{0,n}(X, \beta)\)\textsuperscript{vir} (see [8],[13]).

Let \(X\) be a Calabi-Yau threefold and \(H_1, H_2, H_3 \in H^2(X)\). In the Gromov-Witten setting:

\[
N_\beta(H_1, H_2, H_3) := \int_{\overline{M}_{0,3}(X, \beta)}^\text{vir} e_1^*(H_1)e_2^*(H_2)e_3^*(H_3).
\]

(10) The expected dimension of \(\overline{M}_{0,0}(X, \beta)\) is zero. Let:

\[
N_\beta := \text{deg}(\overline{M}_{0,0}(X, \beta))\text{vir}
\]

(11) By the divisor axiom:

\[
N_\beta(H_1, H_2, H_3) = N_\beta \int_\beta H_1 \int_\beta H_2 \int_\beta H_3.
\]

(12) Let \(C \subset X\) be a smooth rational curve with \(N_{C/X} = \mathcal{O}_C(-1) \oplus \mathcal{O}_C(-1)\). The moduli space \(\overline{M}_{0,0}(X, d[C])\) contains a component of positive dimension, namely \(\overline{M}_{0,0}(C, d)\). The dimension of this component is \(2d - 2\). Consider
the following diagram:

\[ \overline{M}_{0,1}(C, d) \xrightarrow{e_1} C \]
\[ \downarrow \pi \]
\[ \overline{M}_{0,0}(C, d) \]

The sheaf:

\[ \mathcal{V}_d := R^1\pi_* (\mathcal{O}_C(-1) \oplus \mathcal{O}_C(-1)) \]

is locally free of rank \(2d - 2\). Let \( \mathbb{E}_d \) be its top chern class. An assertion of Kontsevich in [7], which was proven by Behrend in [2], states that the part of \([\overline{M}_{0,0}(X, \beta)]^{\text{virt}}\) supported in \(\overline{M}_{0,0}(C, d)\) is Poincaré dual to \(\mathbb{E}_d\). The multiple cover formula in this context says that:

\[ \int_{\overline{M}_{0,0}(C, d)} \mathbb{E}_d = d^{-3} \]

i.e. the curve \(C\) contributes by \(d^{-3}\) to \(N_d[C]\).

The multiple cover formula in this form was proven by Kontsevich [7], Lian-Liu-Yau [9], Manin [10] and Pandharipande [11].

By the divisor property, the multiple cover formula in this context follows from:

\[ \int_{\overline{M}_{0,3}(C, d)} e_1^*(h)e_2^*(h)e_3^*(h)\pi^*(\mathbb{E}_d) = 1 \]

The instanton numbers \(n_\gamma\) are defined inductively by:

\[ N_\beta = \sum_{\gamma = k\beta} n_\gamma k^{-3} \]

The point of this introduction is that the Aspinwall-Morrison calculation deals with concepts and questions that were not well defined at the time. Hence their calculation, although useful and convincing, is incomplete. The purpose of this paper is to relate the two calculations, hence justifying the Aspinwall-Morrison calculation and closing this historic chapter in the subject.

We show in passing the connection between the two formulations of the multiple cover formula for the quintic threefold:

\[ N_d(H, H, H) = d^3N_d = d^3 \sum_{k|d} n_k \left(\frac{k}{d}\right)^3 = \sum_{k|d} n_k k^3 \]

II. A review of the Aspinwall-Morrison calculation. Consider a Calabi-Yau threefold \(X\) and a rational curve \(C \subset X\) such that \(N_{C/X} = \mathcal{O}_C(-1) \oplus \mathcal{O}_C(-1)\). Let:

\[ N_d(C) := \{ f : \mathbb{P}^1 \to X \mid f(\mathbb{P}^1) = C, \deg f = d \} \]
be the space of parameterized maps from $\mathbb{P}^1$ to $X$. Since $C$ is isolated, $N_d(C)$ is a component of the space of all maps from $\mathbb{P}^1$ to $X$.

At a moduli point $[f]$, the tangent space and the obstruction space are given respectively by $H^0(f^*(T_X))$ and $H^1(f^*(T_X))$, i.e. locally $N_d(C)$ is given by $\dim H^1(f^*(T_X))$ equations in the tangent space. The virtual dimension is:

$$\dim H^0(f^*(T_X)) - \dim H^1(f^*(T_X)) = 3.$$  \hspace{1cm} (19)

The space $N_d(C)$ compactifies to $\overline{N}_d(C) = \mathbb{P}^{2d+1}$. Let $\Gamma$ be the compactification of the universal graph $\Gamma \subset N_d(C) \times \mathbb{P}^1 \times C$ and $H$ the hyperplane class in $\overline{N}_d(C)$.

The dimension of $H^1(f^*(T_X))$ is $2d-2$ for any $f$. These vector spaces fit together to form a bundle $U_d$ over $N_d(C)$. Let $p_i$ be the $i$-th projection on $\overline{N}_d(C) \times \mathbb{P}^1 \times C$. The bundle $U_d$ extends to:

$$U_d := R^1 p_1*(p_*^*(T_X|C)|_{\Gamma})$$  \hspace{1cm} (20)

over $\overline{N}_d(C)$. A calculation in $[1]$ yields $U_d = O(-1)^{2d-2}$. Based primarily on considerations from topological field theories, Aspinwall and Morrison asserted that the cycle corresponding to the degree $d$ multiple covers of $C$ is Poincaré dual to $c_{\text{top}}(U_d) = H^{2d-2}$. We will see that this is consistent with the notion of the virtual fundamental class.

Let $H_i \in H^2(X)$ for $i = 1, 2, 3$ and $Z_i$ their Poincaré duals. The space:

$$\{ f \in N_d(C) \mid f(0) = 0 \}$$  \hspace{1cm} (21)

gives rise to a linear subspace of $\overline{N}_d(C)$. Therefore:

$$\# \{ f \in N_d(C) \mid f(0) = 0, f(1) = 1, f(\infty) = \infty \} = \int_{\overline{N}_d(C)} H \cdot H \cdot H \cdot c_{\text{top}}U_d = 1.$$  \hspace{1cm} (22)

It follows that the contribution of $N_d(C)$ to:

$$\# \{ f : \mathbb{P}^1 \to X \mid f_*[\mathbb{P}^1] = d[C], f(0) \in Z_1, f(1) \in Z_2, f(\infty) \in Z_3 \}$$  \hspace{1cm} (23)

is

$$\int_C H_1 \cdot \int_C H_2 \cdot \int_C H_3.$$  \hspace{1cm} (24)

We emphasize that the multiple cover formula in this approach follows from:

$$\int_{\overline{N}_d(C)} H \cdot H \cdot H \cdot c_{\text{top}}U_d = \int_{\overline{N}_d(C)} H^{2d+1} = 1.$$  \hspace{1cm} (25)

**III. The connection to the Gromov-Witten theory.** The main result in this paper is the following:
Proposition 1.0.1. There exists a birational morphism:

\[ \alpha : \overline{M}_{0,3}(C, d) \to \overline{N}_d(C) \]  

such that:

1. \( \alpha_*(e^*_1(h)) = H \) for \( i = 1, 2, 3 \).

2. \( \alpha_*(e^*_1(h)e^*_2(h)e^*_3(h)) = H^3 \).

3. \( \alpha_*(e^*_1(h)e^*_2(h)e^*_3(h)\pi^*(\mathbb{E}_d)) = H^{2d+1} \).

This proposition implies that the equations (15) and (25) are equivalent, hence connecting the Aspinwall-Morrison calculation to the Gromov-Witten theory.

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2. Relation of the Aspinwall-Morrison formula with Gromov-Witten invariants

The space of nonparameterized degree \( d \) maps \( f : \mathbb{P}^1 \to \mathbb{P}^n \) has two particular compactifications that have been employed successfully especially in proving mirror theorems for projective spaces: the nonlinear sigma model (or the graph space):

\[ M^d_n := \overline{M}_{0,0}(\mathbb{P}^n \times \mathbb{P}^1, (d, 1)) \]  

and the linear sigma model:

\[ N^d_n := \mathbb{P}(H^0(O_{\mathbb{P}^1}(d))). \]

Elements of \( N^d_n \) are \((n + 1)\)-tuples \([P_0, ..., P_n]\) of degree \( d \) polynomials in two variables \( w_0, w_1 \). The linear sigma model \( N_d \) is a projective space via the identification \([P_0, ...,] = [\sum a_i w_0^i w_1^d, ...] = [a_0, ..., a_d, ...] \). Note that \( N^1_d = \overline{N}_d(C) \) for \( C \simeq \mathbb{P}^1 \). Let \( H \) be the hyperplane class in \( N^1_d \).

There exists a birational morphism \( \phi : M^d_n \to N^d_n \). We describe this morphism set-theoretically. Let \((C', f) \in M^d_n\). There is a unique component \( C_0 \) of \( C' \) that is mapped with degree 1 to \( \mathbb{P}^1 \). Let \( C_1, ..., C_r \) be the irreducible components of the rest of the curve and \( q_i = (c_i, d_i) \) the nodes of \( C' \) on \( C_0 \). Let \( d - i \) be the degree of the map \( p_2 \circ f : C' \to \mathbb{P}^n \) on \( C_i \) for \( i = 0, 1, ..., r \). Let \( R(w_0, w_1) = \prod_{i=1}^{r}(c_i w_1 - d_i w_0)^{d_i} \). If the restriction of the map \( p_2 \circ f \) is given by \([Q_0, ..., Q_n]\) then:

\[ \phi(C', f) := [RQ_0, ..., RQ_n]. \]

A proof of the fact that \( \phi \) is a morphism is given by J. Li in [4].

The first step in connecting the Aspinwall-Morrison calculation to Gromov-Witten invariants is showing that \( M^d_n \) and \( N^d_n \) are birational models for \( \overline{M}_{0,3}(\mathbb{P}^n, d) \).

Lemma 2.0.1. There exists a birational map \( \psi : \overline{M}_{0,3}(\mathbb{P}^n, d) \to M^d_n \).
Proof. Consider the following diagram:
\[
\begin{array}{ccc}
\overline{M}_{0,4}(\mathbb{P}^n, d) & \xrightarrow{(\hat{\pi}, e_4)} & \overline{M}_{0,4} \times \mathbb{P}^n \\
\downarrow \pi_4 & & \downarrow \\
\overline{M}_{0,3}(\mathbb{P}^n, d).
\end{array}
\]
Since \(\overline{M}_{0,4} \simeq \mathbb{P}^1\) and \(e_4\) is stable in the fibers of \(\pi_4\), the above diagram exhibits a stable family of maps of degree \((1, d)\) parametrized by \(\overline{M}_{0,3}(\mathbb{P}^n, d)\). Universal properties of \(M^n\) yield a morphism:
\[
\psi : \overline{M}_{0,3}(\mathbb{P}^n, d) \to M^n_d.
\]
The map \(\psi\) is an isomorphism in the smooth locus, hence it is a birational map.\(^\dagger\)

Let \(\pi_4 : \overline{M}_{0,4} \to \overline{M}_{0,3} = \{pt\}\) be the map that forgets the last marked point and \(\sigma_i\) be the section of the \(i\)-th marked point for \(i = 1, 2, 3\). Choose coordinates on \(\overline{M}_{0,4} \simeq \mathbb{P}^1\) such that the images of these three sections are respectively \(0 = [1, 0], \infty = [0, 1], 1 = [1, 1]\). Let
\[
(31) \quad \alpha := \phi \circ \psi : \overline{M}_{0,3}(\mathbb{P}^n, d) \to N^n_d.
\]

Proposition 2.0.2. Let \(h\) be the hyperplane class of \(\mathbb{P}^n\).
1. \(\alpha_4(e_i^*(h)) = H\) for \(i = 1, 2, 3\).
2. \(\alpha_4(e_1^*(h)e_2^*(h)e_3^*(h)) = H^3\)

Proof. Let
\[
(32) \quad \nu_1 : N_d \to \mathbb{P}^n
\]
be a rational map defined by
\[
(33) \quad \nu_1([P_0, P_1, ..., P_n]) = [P_0(1, 0), P_1(1, 0), ..., P_n(1, 0)].
\]
This map is defined in the complement \(U\) of a codimension \(n + 1\) linear subspace \(P(W_1)\) of \(N^n_d\). Clearly \(\nu_1^*(h) = H\) on \(U\). The preimage \(D_{1,23}\) of \(P(W_1)\) in \(\overline{M}_{0,3}(\mathbb{P}^n, d)\) is a sum of \(d\) boundary divisors \(D_{\{x_1\}, \{x_2, x_3\}, d_1, d_2}\) with \(d_1 > 0\) and \(d_1 + d_2 = d\). The evaluation map \(e_1\) over \(U\) factors through the rational map \(\nu_1\). It follows that
\[
(34) \quad e_1^*(h) = \alpha^*(H) + D_1,
\]
where \(D_1\) is a divisor supported in \(D_{1,23}\). Using the evaluations at 1 and \(\infty\) on \(N^n_d\), we obtain:
\[
(35) \quad e_2^*(h) = \alpha^*(H) + D_2
\]
\(^\dagger\)It can be shown that \(D_1 = -\sum d_i D_{\{x_1\}, \{x_2, x_3\}, d_1, d - d_1}\) but this is not important in this paper.
and
\[(36) \quad e^*_3(h) = \alpha^*(H) + D_3,\]
where \(D_2\) is a divisor supported in \(D_{2,13}\) and \(D_3\) is supported in \(D_{3,12}\).

The \(\psi\)-image of \(D(\{x_1\}, \{x_2, x_3\}, d_1, d_2)\) does not detect the movement of the marking \(x_1\) along its incident component, hence it is a codimension 2 cycle in \(M^n_d\). It follows that \(\psi_*(D_1) = 0\). Similarly \(\psi_*(D_2) = 0\) and \(\psi_*(D_3) = 0\). Both \(\psi\) and \(\phi\) are birational hence by the projection formula:
\[(37) \quad \alpha_*(e^*_i(h)) = H\]
for \(i = 1, 2, 3\).

Let \(D' \in D_{1,23}, D'' \in D_{2,13}, D''' \in D_{3,12}\) be irreducible boundary divisors. The intersection of any two of them either is 0 or its image is a codimension 4 cycle in \(M^n_d\). It follows that:
\[(38) \quad \psi_*(D'D'') = \psi_*(D'D''') = \psi_*(D''D''') = 0.\]

Notice also that:
\[(39) \quad D'D''D''' = 0.\]

The projection formula yields:
\[(40) \quad \psi_*(e^*_1(h)e^*_2(h)e^*_3(h)) = \psi_*(\prod_i (\psi^*(\phi^*(H)) + D_i)) = \prod_i (\phi^*(H)) = \phi^*(H^3).\]

The lemma follows from the fact that \(\phi\) is a birational map.†

Return now to the case \(n = 1\) of our interest.

Let \(\rho : M^1_d \to \overline{M}_{0,3}(C, d)\) be the natural morphism. The composition:
\[(41) \quad \rho \circ \psi : \overline{M}_{0,3}(C, d) \to \overline{M}_{0,0}(C, d)\]
is the map \(\pi\) that forgets the 3 marked points and stabilizes the source curve. Recall Kontsevich’s obstruction bundle \(V_d\) on \(\overline{M}_{0,0}(C, d)\). Its fiber is \(H^{1}(C', f^*(\mathcal{O}(-1) \oplus \mathcal{O}(-1)))\). Its top chern class is \(E_d\). We are now ready to exhibit the connection between the Aspinwall-Morrison calculation and Gromov-Witten invariants.

**Proposition 2.0.3.** \(\alpha_*(e^*_1(h)e^*_2(h)e^*_3(h)\pi^*(E_d)) = H^{2d+1}\).

**Proof.** Let \(E_d\) be the top chern class of the bundle \(\rho^*(V_d)\) on \(M^1_d\). Recall from part II of the introduction that \(H^{2d-2}\) is the top chern class of the Aspinwall-Morrison obstruction bundle \(U_d\) on \(N^1_d\). It is shown in [9] that \(\phi_*(E_d) = H^{2d-2}\). On the other hand \(\psi^*(E_d) = \pi^*(E_d)\). But \(\psi\) is birational, hence by the projection formula \(\psi_*(\pi^*(E_d)) = E_d\).
We compute:

\[ \alpha^* \left( \prod_i e^*_i (h^* (\psi^* (E_d))) \right) = \alpha^* \left( \prod_i e^*_i (h^*) \psi^* (E_d) \right) = \phi^* (\psi^* (\prod_i e^*_i (h^*)) E_d) \]

\[ = \phi^* (\phi^* (H^3) E_d) = H^3 \phi^* (E_d) = H^3 H^{2d-2} = H^{2d+1}. \]

The proposition is proven.†

The last proposition yields:

\[ \int_{\overline{M}_{0,3}(C,d)} \prod_{i=1}^{3} e^*_i (h^*) E_d = \int_{N_d(C)} \alpha^* (\prod_{i=1}^{3} e^*_i (h^*) \psi^* (E_d)) = \int_{N_d(C)} H^{2d+1} = 1, \]

i.e. the Aspinwall-Morrison calculation is a pushforward of Kontsevich’s calculation from \( \overline{M}_{0,3}(C,d) \) to the projective space \( N_d(C) \).

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