GIVENTAL’S LAGRANGIAN CONE AND $S^1$-EQUIVARIANT
GROMOV–WITTEN THEORY

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Abstract. In the approach to Gromov–Witten theory developed by Givental, genus-zero Gromov–Witten invariants of a manifold $X$ are encoded by a Lagrangian cone in a certain infinite-dimensional symplectic vector space. We give a construction of this cone, in the spirit of $S^1$-equivariant Floer theory, in terms of $S^1$-equivariant Gromov–Witten theory of $X \times \mathbb{P}^1$. This gives a conceptual understanding of the “dilaton shift”: a change-of-variables which plays an essential role in Givental’s theory.

1. Introduction

It has long been understood that it is a good idea to arrange Gromov–Witten invariants into generating functions which reflect their origins in physics: many operations in Gromov–Witten theory which seem complicated when viewed at the level of individual invariants correspond to the application of rather simpler differential operators to these generating functions. A recent insight of Givental is that such differential operators, which can themselves appear quite complicated, are often the quantizations of very simple linear symplectic transformations of a certain symplectic vector space. This point of view — Givental’s quantization formalism [22, 23] — has been a crucial ingredient in several recent advances in the subject. These include the proof of the Virasoro conjecture for toric Fano manifolds [21], the computation of twisted Gromov–Witten invariants [42], the proof of a Quantum Hirzebruch–Riemann–Roch theorem relating quantum extraordinary cohomology to quantum cohomology [8, 9], and the construction of integrable hierarchies controlling the total descendant potentials of certain Frobenius manifolds [24, 26, 39].

The symplectic vector space associated to the Gromov–Witten theory of an almost-Kähler manifold $X$ is the space of Laurent series

$$\mathcal{H} = H^\bullet(X) \otimes \mathbb{C}(z^{-1})$$

equipped with the symplectic form

$$\Omega(f, g) = \text{Res}_{z=0} \left(f(-z), g(z)\right) \, dz.$$

Here $(\cdot, \cdot)$ is the Poincaré pairing on $H^\bullet(X)$. Generating functions for Gromov–Witten invariants — the genus-$g$ Gromov–Witten potentials of $X$ and the total descendant potential of $X$ — are regarded as functions on $\mathcal{H}_+ = H^\bullet(X)[z]$ via a
change of variables, called the dilaton shift, described in equation 3 below. Genus-zero Gromov–Witten invariants are encoded by a certain Lagrangian submanifold $\mathcal{L}$ of $X$, defined in section 2.3 below. This submanifold $\mathcal{L}$ has a very tightly-constrained geometry: it is a Lagrangian cone ruled by a finite-dimensional family of isotropic subspaces $[3, 13].$

We currently lack a conceptual understanding of why the quantization formalism is so effective. It makes sense, therefore, to look for a geometric interpretation of the ingredients of the formalism — of the symplectic vector space $\mathcal{H}$, the submanifold $\mathcal{L}$, and the dilaton shift. In this paper we give a simple and geometric construction of the submanifold $\mathcal{L}$ in terms of the $S^1$-equivariant Gromov–Witten theory of the space $X \times \mathbb{P}^1$. This gives rise to the dilaton shift in a natural way. Our construction suggests that $\mathcal{H}$ should be thought of as the $S^1$-equivariant Floer homology of the loop space of $X$; this is discussed further in Section 3 below.

The idea of the construction is as follows. There is an “evaluate at infinity” map $ev_{\infty} : (X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)} \to X$ from an open set in the moduli space of stable maps to $X \times \mathbb{P}^1$ of bidegree $(d, 1)$ from genus-zero curves with $n$ marked points. This open set is the locus of stable maps $f : \Sigma \to X \times \mathbb{P}^1$ such that the preimage $f^{-1}(X \times \{\infty\})$ consists of a single unmarked smooth point — so there are no bubbles or marked points over $\infty \in \mathbb{P}^1$ — and the map $ev_{\infty}$ records the point of $X$ mapped to by $f^{-1}(X \times \{\infty\})$. Although $ev_{\infty}$ is not proper, it is equivariant with respect to the $S^1$-action on $(X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)}$ coming from the $S^1$-action of weight $-1$ on the second factor of $X \times \mathbb{P}^1$ and the trivial $S^1$-action on $X$. This allows us to define a push-forward

$$(ev_{\infty})_* : H^*_S \left((X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)}\right) \otimes \mathbb{C}(z^{-1}) \to H^*(X) \otimes \mathbb{C}(z^{-1}),$$

where $H^*_S(pt) = \mathbb{C}[z]$; the restriction of the map $ev_{\infty}$ to $S^1$-fixed sets is proper, so we can define the push-forward using fixed-point localization. To push an equivariant class forward along $ev_{\infty}$ we first restrict it to the $S^1$-fixed set in $(X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)}$, then cap with the virtual fundamental class of the fixed set, then divide by the $S^1$-equivariant Euler class of the virtual normal bundle, and then push forward (in the usual sense) along the map $ev_{\infty}$ from the $S^1$-fixed set to $X$. One can think of this operation as a virtual push-forward in $S^1$-equivariant Borel-Moore-Tate homology; it is defined only over the field of fractions $\mathbb{C}(z)$ of $H^*_S(pt)$, and not over $H^*_S(pt)$ itself, because we need to divide by the Euler class of the virtual normal bundle. The Lagrangian cone $\mathcal{L}$ is the image of a certain class

$$(-z) \sum_{d \in H_2(X, \mathbb{Z})} \frac{Q^d}{n!} \prod_{i=1}^n ev^*_i t(\psi_i) \in \bigoplus_{d \in H_2(X, \mathbb{Z})} H^*_S \left((X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)}\right),$$

defined in detail in Section 2 below, under this push-forward.

The dilaton shift arises here in the following way: the $S^1$-fixed set in the space $(X \times \mathbb{P}^1)^{op}_{0, n, (d, 1)}$ can almost always be identified with the space $X_{0, n+1, d}$ of degree-$d$ stable maps to $X$ from genus-zero curves with $n + 1$ marked points. There are two exceptions to this, however: when $(n, d) = (0, 0)$ and when $(n, d) = (1, 0)$, the moduli space $X_{0, n+1, d}$ is empty but the $S^1$-fixed set is a copy of $X$. It is the contributions to the push-forward of 3 coming from these exceptional fixed loci
which give rise to the dilaton shift. In the notation of Section 2, the push-forward of $\mathcal{L}$ is
\[
-z + t(z) + \sum_{d \in H_2(X;\mathbb{Z}) \atop n \geq 0} \frac{Q^d}{n!} (\text{ev}_{n+1})_* \left[ [X_{0,n+1,d}]_{\text{vir}} \cap \left( \prod_{i=1}^{n} \text{ev}_i^* t(\psi_i) \right) \cdot \frac{1}{-z - \psi_{n+1}} \right].
\]
This makes the change of variables (6) seem very natural.

We should emphasize that none of the geometric ingredients here are new. The observation that a product of two copies of the $J$-function — a certain generating function for genus-zero Gromov–Witten invariants — can be computed by fixed-point localization on the graph space $X \times \mathbb{P}^1$ was, or was equivalent to, a crucial step in proving mirror theorems for toric varieties [3,19,20,30–32]. The equivariant push-forward described above was introduced by Braverman [4] in order to extract one copy of the $J$-function of a flag manifold from the corresponding graph space. The content of this paper is the observation that when Braverman’s construction is extended to “big quantum cohomology” and to include gravitational descendants, the dilaton shift emerges automatically.

Experts in the subject may wish to stop reading here, as what follows is routine. Section 2 contains an introduction to Givental’s quantization formalism. The details of the construction of $\mathcal{L}$ are in Theorem 1 and Section 3. The localization theorem which we need does not appear to have been written down anywhere, so we prove it in the Appendix.

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2. Givental’s Quantization Formalism

We begin by describing the quantization formalism. We fix notation for Gromov–Witten invariants in section 2.1 and discuss the framework for working with higher-genus invariants in section 2.2. The latter section is not logically necessary: the reader who is familiar with Givental’s approach or uninterested in the surrounding context should skip to section 2.3 where the genus-zero picture is described.

2.1. Gromov–Witten Invariants. Let $X$ be a smooth projective variety. The Gromov–Witten invariants of $X$ are certain intersection numbers in moduli spaces of stable maps (see e.g. [16,34,36,38,41]). Let $X_{g,n,d}$ denote the moduli space of stable maps to $X$ of degree $d \in H_2(X;\mathbb{Z})$ from curves of genus $g$ with $n$ marked points.
points, and let \([X_{g,n,d}]_{\text{vir}}\) be its virtual fundamental class \([1, 2, 3, 7]\). The moduli space comes equipped with evaluation maps

\[ \text{ev}_i : X_{g,n,d} \to X \quad i \in \{1, \ldots, n\} \]

and universal cotangent line bundles

\[ L_i \to X_{g,n,d} \quad i \in \{1, \ldots, n\} \]

at each marked point. We denote the first Chern class of \(L_i\) by \(\psi_i\). Gromov–Witten invariants are intersection numbers of the form

\[ \int_{[X_{g,n,d}]_{\text{vir}}} \prod_{i=1}^{n} \text{ev}_i^*(\alpha_i) \cdot \psi_i^{k_i}, \]

where \(\alpha_1, \ldots, \alpha_n\) are cohomology classes on \(X\) and \(k_1, \ldots, k_n\) are non-negative integers. If any of the \(k_i\) are non-zero, such invariants are called gravitational descendants.

The genus-\(g\) descendant potential of \(X\) is a generating function for Gromov–Witten invariants:

\[ F_g^X(t_0, t_1, \ldots) = \sum_{d \in H_2(X; \mathbb{Z})} \sum_{n \geq 0} \frac{Q^d}{n!} \int_{[X_{g,n,d}]_{\text{vir}}} \prod_{i=1}^{n} \text{ev}_i^* t(\psi_i). \]

Here \(t_0, t_1, \ldots\) are cohomology classes on \(X\); \(t(\psi) = t_0 + t_1 \psi + t_2 \psi^2 + \ldots\), so that

\[ \text{ev}_i^* t(\psi_i) = \text{ev}_i^* (t_0) + \text{ev}_i^* (t_1) \cdot \psi_i + \text{ev}_i^* (t_2) \cdot \psi_i^2 + \ldots; \]

and \(Q^d\) is the representative of \(d\) in the Novikov ring \([13, \text{III 5.2.1}]\), which is a certain completion of the group ring of \(H_2(X; \mathbb{Z})\). If we pick a basis \(\{\phi_1, \ldots, \phi_N\}\) for \(H^\bullet(X; \mathbb{C})\) and write

\[ t_i = t_i^1 \phi_1 + \ldots + t_i^N \phi_N \]

then

\[ F_g^X(t_0, t_1, \ldots) = \sum_{d \in H_2(X; \mathbb{Z})} \sum_{k_1, \ldots, k_n} \frac{Q^d}{n!} \int_{[X_{g,n,d}]_{\text{vir}}} \prod_{i=1}^{n} \text{ev}_i^* (\phi_{\alpha_i}) \cdot \psi_i^{k_i}, \]

so we can regard \(F_g^X\) as a formal power series with Taylor coefficients given by Gromov–Witten invariants of \(X\). The total descendant potential of \(X\)

\[ D_X(t_0, t_1, \ldots) = \exp \left( \sum_{g \geq 0} h^{g-1} F_g^X(t_0, t_1, \ldots) \right) \]

is a generating function for Gromov–Witten invariants of all genera.

2.2. The quantization formalism. Consider the space

\[ \mathcal{H} = H^\bullet(X)((z^{-1})) \]

of cohomology-valued Laurent series, equipped with the symplectic form

\[ \Omega(f, g) = \text{Res}_{z=0} \left( f(-z), g(z) \right) dz. \]

Here and from now on we work over a ground ring \(\Lambda\) which is the tensor product of the Novikov ring with \(\mathbb{C}\): we take cohomology with coefficients in \(\Lambda\), the Poincaré
pairing $(\cdot, \cdot)$ and the symplectic form are $\Lambda$-valued, and so on. The space $\mathcal{H}$ is the direct sum of Lagrangian subspaces

$$\mathcal{H}_+ = H^*(X)[z], \quad \mathcal{H}_- = z^{-1}H^*(X)[z^{-1}].$$

A general element of $\mathcal{H}$ takes the form

$$\sum_{k=0}^\infty \sum_{\mu=1}^N q^{\mu}_k \phi_\mu z^k + \sum_{l=0}^\infty \sum_{\nu=1}^N p^{\nu}_l \phi_\nu (-z)^{-1-l}$$

where $\{\phi_1, \ldots, \phi_N\}$ is our basis for $H^*(X)$, we set $g_{\alpha\beta} = (\phi_\alpha, \phi_\beta)$, define $g^{\alpha\beta}$ to be the $(\alpha, \beta)$-entry of the matrix inverse to that with $(\alpha, \beta)$-entry $g_{\alpha\beta}$, and raise indices using $g^{\alpha\beta}$:

$$\phi^{\nu} = \sum_{\lambda=1}^N g^{\nu\lambda} \phi_\lambda.$$

Equation (5) defines Darboux co-ordinates $\{q^{\mu}_k, p^{\nu}_l\}$ on $\mathcal{H}$ which are compatible with the polarization $\mathcal{H} = \mathcal{H}_+ \oplus \mathcal{H}_-$.

To each linear infinitesimal symplectic transformation $A \in \mathfrak{sp}(\mathcal{H})$ we associate a differential operator — the quantization $\widehat{A}$ — constructed as follows. The quadratic Hamiltonian $h_A : f \mapsto \frac{1}{2} \Omega(Af, f)$ can be written as a linear combination of quadratic monomials in the Darboux co-ordinates $\{q^{\mu}_k, p^{\nu}_l\}$. We set

$$\widehat{q^\mu_k q^\nu_l} = \frac{q^{\mu}_k q^{\nu}_l}{\hbar}, \quad \widehat{p^\mu_k q^\nu_l} = q^{\nu}_l \frac{\partial}{\partial q^{\mu}_k}, \quad \widehat{p^\mu_k p^\nu_l} = \hbar \frac{\partial}{\partial q^{\mu}_k} \frac{\partial}{\partial q^{\nu}_l},$$

and extend by linearity, defining the quantization $\widehat{A}$ of $A$ to equal $\widehat{h_A}$. The quantized operator $\widehat{A}$ acts on certain formal power series in the variables $q^{\alpha}_k$, where $\alpha \in \{1, \ldots, N\}$ and $k \geq 0$.

Let

$$q_k = \sum_{\lambda=1}^N q^{\lambda}_k \phi_\lambda \quad k = 0, 1, 2, \ldots,$$

and

$$\mathbf{q}(z) = q_0 + q_1 z + q_2 z^2 + \ldots.$$

Quantized infinitesimal symplectic transformations $\widehat{A}$ act on certain formal functions of $\mathbf{q}(z)$ — in other words, on certain formal power series in the $q^{\alpha}_k$ — whereas the total descendant potential $D_X(t_0, t_1, \ldots)$ is a formal function of

$$\mathbf{t}(z) = t_0 + t_1 z + t_2 z^2 + \ldots$$

— or in other words, a formal power series in the variables $t^{\alpha}_k$ from (4). We let quantized operators $\widehat{A}$ act on the total descendant potential $D_X(t_0, t_1, \ldots)$ via the identification

$$\mathbf{q}(z) = \mathbf{t}(z) - z.$$

This change of variables is called the dilaton shift.

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2Since the symplectic space $\mathcal{H}$ is infinite-dimensional, quantizations $\widehat{A}$ in general contain infinite sums of differential operators. The application of a general quantized infinitesimal symplectic transformation to a general formal power series in the variables $q^{\alpha}_k$ is not well-defined, but it is easy to check that the operations used in the Example below do in fact make sense.
This framework allows one to express many operations which arise in Gromov–Witten theory in terms of the quantizations of very simple linear symplectic transformations of $\mathcal{H}$. One example of this occurs in the Gromov–Witten theory of a point.

**Example: The Virasoro Conjecture.** Let $X$ be a point. The corresponding symplectic space is

$$\mathcal{H} = \mathbb{C}(\langle z^{-1} \rangle), \quad \Omega(f, g) = \text{Res}_{z=0} f(-z)g(z) \, dz,$$

and Darboux co-ordinates $\{q_k, p_l\}$ on $(\mathcal{H}, \Omega)$ are given by

... $p_0 - 1/2 \sum_{l=0}^{n-1} (-1)^l \frac{\Gamma(n - l + \frac{1}{2})}{\Gamma(-l - \frac{1}{2})} \partial_t \partial t_{n-l-1}$ $n \geq 0$.

The quantizations $\hat{l}_n$ are the differential operators

$$\frac{\partial}{\partial t_0} - \sum_{k \geq 1} l_k \frac{\partial}{\partial t_{k-1}} + \frac{l_0^2}{2\hbar} \quad n = -1$$

Note that the dilaton shift (6) plays an essential role here, as without it these differential operators would not be quadratic in $p_\alpha$ and $q_\beta$. The Virasoro Conjecture for Gromov–Witten invariants of a point (see e.g. [17]) asserts that

$$\left( \hat{l}_n - \frac{\delta_{n,0}}{16} \right) D_{pt}(t_0, t_1, \ldots) = 0, \quad n \geq -1.$$

This is equivalent [11] to Witten’s Conjecture [43], proved by Kontsevich [35].

### 2.3. The genus-zero picture

So far we have considered a formalism for working with Gromov–Witten invariants of all genera. This involves quantized symplectic transformations applied to generating functions for the invariants. The semiclassical limit of this framework involves *unquantized* symplectic transformations applied to certain Lagrangian submanifolds of $\mathcal{H}$. This is how the Lagrangian submanifold $\mathcal{L}$ from the Introduction enters the theory.
It is easy to see that if
\[ D(s) = \exp \left( \sum_{g \geq 0} h^{g-1} F^g(s) \right) \]
is a one-parameter family of formal power series in the variables \( q^\mu_k \) such that
\[ \frac{d}{ds} D(s) = \hat{A} D(s) \]
for some \( A \in \mathfrak{sp}(H) \), then the formal germ of a Lagrangian submanifold of \( H \) given in Darboux co-ordinates (5) by
\[ p^\mu_l = \partial F_0^0(s) \partial q^\nu_l \]
evolves with \( s \) under the Hamiltonian flow of \( h_A \). We thus consider the formal germ of a Lagrangian submanifold \( L \) defined by
\[ p^\mu_l = \frac{\partial F^0_X}{\partial q^\nu_l}, \]
where we regard \( F^0_X(t_0, t_1, \ldots) \) as a formal power series in the \( q^\nu_l \) via the dilaton shift (6). The formal germ \( L \) is defined for \( q(z) \) near \(-z\). It corresponds, under the identification of \( H = H_+ \oplus H_- \) with \( T^*H_+ = H_+ \oplus H_\nu^\star \) coming from the polarization, to the graph of the differential of the genus-zero descendant potential \( F^0_X \). \( L \) therefore encodes genus-zero Gromov–Witten invariants of \( X \). A general point of \( L \) takes the form
\[ q(z) + \sum_{d \in H_2(X; \mathbb{Z})} \frac{Q^d}{n!} (\text{ev}_{n+1})_* \left[ [X_{0,n+1,d}]^\text{vir} \cap \left( \prod_{i=1}^{i=n} \text{ev}_i^* t(\psi_i) \right) \cdot \frac{1}{z - \psi_{n+1}} \right]. \]

To see this, expand \( \frac{1}{z - \psi_{n+1}} \) as a power series in \( z^{-1} \) and compare (6) with (3) and (7).

3. The Localization Calculation

We begin this section by giving a precise definition of the virtual push-forward described in the Introduction. We then state Theorem 1. The proof of Theorem 1, which is a straightforward application of the virtual localization result of Graber and Pandharipande [25], is contained in section 3.2.

3.1. A virtual push-forward. Given schemes \( Y \) and \( Z \) with \( \mathbb{C}^\times \)-action, an equivariant map \( f : Y \to Z \) such that the induced map on fixed sets is proper gives a push-forward
\[ f_* : H^\bullet_{BM}(Y) \otimes \mathbb{C}(z) \to H^\bullet_{BM}(Z) \otimes \mathbb{C}(z) \]
\[ \text{We have switched from } S^1 \text{-actions to } \mathbb{C}^\times \text{-actions in order to make use of the virtual localization result [24].} \]
in $\mathbb{C}^\times$-equivariant Borel–Moore homology \cite{1}. $\mathbb{C}(z)$ here is the field of fractions of $H^{\cdot}_{\mathbb{C}^\times}(pt) = \mathbb{C}[z]$. The localization theorem (see \cite{13} and the Appendix) implies that the maps

$$(i_Y)_* : H^{\cdot}_{\mathbb{C}^\times, BM}(Y^{\mathbb{C}^\times}) \to H^{\cdot}_{\mathbb{C}^\times, BM}(Y), \quad (i_Z)_* : H^{\cdot}_{\mathbb{C}^\times, BM}(Z^{\mathbb{C}^\times}) \to H^{\cdot}_{\mathbb{C}^\times, BM}(Z)$$

induced by the inclusions $i_Y : Y^{\mathbb{C}^\times} \to Y$, $i_Z : Z^{\mathbb{C}^\times} \to Z$ of $\mathbb{C}^\times$-fixed sets become isomorphisms after tensoring with $\mathbb{C}(z)$. The localization theorem (see \cite{13} and the Appendix) implies that the maps

$$((i_Y)_*)^{-1} : H^{\cdot}_{\mathbb{C}^\times, BM}(Y^{\mathbb{C}^\times}) \otimes \mathbb{C}(z) \longrightarrow H^{\cdot}_{\mathbb{C}^\times, BM}(Z^{\mathbb{C}^\times}) \otimes \mathbb{C}(z)$$

where the bottom horizontal arrow is the usual proper push-forward. When the map $f$ is proper, (9) agrees with the usual push-forward.

If $Y$ and $Z$ are smooth $\mathbb{C}^\times$-varieties and $f : Y \to Z$ is equivariant and proper on fixed sets as before then this construction gives a push-forward in equivariant cohomology

$$f_* : H^{\cdot}_{\mathbb{C}^\times}(Y) \otimes \mathbb{C}(z) \to H^{\cdot}_{\mathbb{C}^\times}(Z) \otimes \mathbb{C}(z)$$

which raises degree by $2 \dim_{\mathbb{C}}(Z) - 2 \dim_{\mathbb{C}}(Y)$. This is by definition the composition

$$H^{\cdot}_{\mathbb{C}^\times}(Y) \otimes \mathbb{C}(z) \xrightarrow{f_*} H^{\cdot}_{\mathbb{C}^\times}(Z) \otimes \mathbb{C}(z) \xrightarrow{(i_Z)_*} H^{\cdot}_{\mathbb{C}^\times, BM}(Z^{\mathbb{C}^\times}) \otimes \mathbb{C}(z)$$

where the vertical arrows are Poincaré duality and the bottom horizontal arrow is the push-forward (9).

In the case we wish to consider, $Y$ will be an open subset of a moduli space of stable maps. This need not be smooth, but it does carry a $\mathbb{C}^\times$-equivariant perfect obstruction theory: it is “virtually smooth”. Given a $\mathbb{C}^\times$-scheme $Y$ equipped with a $\mathbb{C}^\times$-equivariant perfect obstruction theory, a smooth $\mathbb{C}^\times$-variety $Z$, and an equivariant map $f : Y \to Z$ which is proper on fixed sets, we define the virtual push-forward

$$f_* : H^{\cdot}_{\mathbb{C}^\times}(Y) \otimes \mathbb{C}(z) \to H^{\cdot}_{\mathbb{C}^\times}(Z) \otimes \mathbb{C}(z)$$

as follows. The obstruction theory determines a virtual fundamental class \cite{1,2,37} in the equivariant Chow group $A^{\mathbb{C}^\times}_{\text{vdim}(Y)}(Y)$, where $\text{vdim}(Y)$ is the virtual dimension, and hence (via the cycle map) gives a class in equivariant Borel–Moore homology

$$[Y]_{\text{vir}} \in H^{\cdot}_{\text{2vdim}(Y), BM}(Y).$$
The virtual push-forward is defined to be the composition
\[
\begin{array}{ccc}
H^\bullet_{C^\times} (Y) \otimes \mathbb{C}(z) & \xrightarrow{f_*} & H^\bullet(Z) \otimes \mathbb{C}(z) \\
\star \quad & \downarrow \quad & \downarrow \\
H^\bullet_{BM}(Y) \otimes \mathbb{C}(z) & \longrightarrow & H^\bullet_{BM}(Z) \otimes \mathbb{C}(z)
\end{array}
\]
where the left-hand vertical arrow is cap product with the class \([Y]^{vir}\), the right-hand vertical arrow is Poincaré duality, and the bottom horizontal arrow is the push-forward \((\overline{1})\). The virtual push-forward raises degree by \(2 \dim \mathbb{C}(Z) - 2 \dim(Y)\).

Once appropriate definitions are in place, the construction extends without change to the case (which we will need below) in which \(Y\) is a Deligne–Mumford quotient stack rather than a scheme; see the Appendix for details.

The virtual localization result of Graber and Pandharipande \([25]\) implies that, under a mild technical hypothesis \(^5\),
\[
[Y]^{vir} = (i_Y)_* \left[ \sum \frac{[Y_j]^{vir}}{e(N_j^{vir})} \right] \in H^\bullet_{BM}(Y) \otimes \mathbb{C}(z).
\]
The sum here is over components \(Y_j\) of the \(C^\times\)-fixed locus in \(Y\). The virtual fundamental classes \([Y_j]^{vir}\) and virtual normal bundles \(N_j^{vir}\) are determined by the obstruction theory; \(e\) here denotes the \(C^\times\)-equivariant Euler class. If we write \(f_j\) for the restriction of \(f : Y \to Z\) to the \(C^\times\)-fixed component \(Y_j\) then \((\overline{1})\) implies that we can write the virtual push-forward of \(\alpha \in H^\bullet_{C^\times}(Y) \otimes \mathbb{C}(z)\) as
\[
f_*(\alpha) = \sum (f_j)_* \left[ \frac{[Y_j]^{vir} \cap \alpha|_{Y_j}}{e(N_j^{vir})} \right].
\]

Consider now the open subset \((X \times \mathbb{P}^1)^{op}_{0,n,(d,1)}\) of the moduli space \((X \times \mathbb{P}^1)_{0,n,(d,1)}\) consisting of those stable maps \(f : \Sigma \to X \times \mathbb{P}^1\) such that the preimage \(f^{-1}(X \times \{\infty\})\) is a single unmarked smooth point \(x_\infty\). Consider the \(C^\times\)-action on moduli space coming from the trivial \(C^\times\)-action on \(X\) and the \(C^\times\)-action of weight \(-1\) on \(\mathbb{P}^1\). The space \((X \times \mathbb{P}^1)_{0,n,(d,1)}\) carries a canonical \(C^\times\)-equivariant perfect obstruction theory, and so the \(C^\times\)-invariant open subset \((X \times \mathbb{P}^1)^{op}_{0,n,(d,1)}\) does too. The “evaluate at infinity” map
\[
ev_\infty : (X \times \mathbb{P}^1)^{op}_{0,n,(d,1)} \to X
\]
which sends the stable map \(f : \Sigma \to X \times \mathbb{P}^1\) to \(f(x_\infty)\) is \(C^\times\)-equivariant and proper on fixed sets. The virtual push-forwards along the maps \(\ev_\infty\) assemble to give a map
\[
\Ev_\infty : \bigoplus_{d \in H^2(X,\mathbb{Z})} H^\bullet_{S^1}\left((X \times \mathbb{P}^1)^{op}_{0,n,(d,1)}\right) \to \mathcal{H}.
\]
We are now ready to state our result.

\(^5\)They require that \(Y\) admit a \(C^\times\)-equivariant embedding into a non-singular Deligne–Mumford stack. This is the case when \(Y\) is an open subset of a moduli stack of stable maps to a \(C^\times\)-variety; see Appendices A and C of \([25]\).
Theorem 1. $\mathcal{L}$ is the image under $\text{Ev}_\infty$ of the class

$$(-z) \sum_{d \in H_2(X;\mathbb{Z})} \frac{Q_d}{n!} \prod_{i=1}^{i=n} \text{ev}_i^* \mathbf{t}(\psi_i) \in \bigoplus_{d \in H_2(X;\mathbb{Z})}^{n \geq 0} H^*_\mathbb{S}_X \left( (\mathbb{P}^1\mid_{0,n}(d,1)) \right).$$

3.2. The Proof of Theorem 1. This is a straightforward application of the formula (11) for the virtual push-forward. The calculations are similar to, but easier than, those occurring in section 4 of [25].

Case 1: $(n,d) \notin \{(0,0),(1,0)\}$. The $\mathbb{C}^\times$-fixed locus in $(X \times \mathbb{P}^1)_{0,n(d,1)}^{op}$ consists of stable maps from nodal curves such that exactly one component of the curve is mapped with degree 1 to $\{x_\infty\} \times \mathbb{P}^1 \subset X \times \mathbb{P}^1$, and the rest of the curve is mapped to $X \times \{0\}$. We identify the fixed locus with the moduli space $\mathcal{X}_{0,n+1,d}$. The $\mathbb{C}^\times$-fixed part of the perfect obstruction theory on $(X \times \mathbb{P}^1)_{0,n(d,1)}^{op}$ coincides with the usual perfect obstruction theory on $\mathcal{X}_{0,n+1,d}$, and the virtual normal bundle to the fixed locus is

$$C_{(-1)} \oplus (L_{n+1} \otimes C_{(-1)})$$

where $C_{(-1)}$ denotes the trivial bundle over $\mathcal{X}_{0,n+1,d}$ with $\mathbb{C}^\times$-weight $-1$. Thus

$$\text{(12)} \quad (\text{ev}_\infty)_* \left[ (-z) \prod_{i=1}^{i=n} \text{ev}_i^* \mathbf{t}(\psi_i) \right] =$$

$$= (\text{ev}_{n+1})_* \left[ [\mathcal{X}_{0,n+1,d}]^{vir} \cap \left( \prod_{i=1}^{i=n} \text{ev}_i^* \mathbf{t}(\psi_i) \right) \cdot \frac{1}{-z - \psi_{n+1}} \right]$$

Case 2: $(n,d) = (1,0)$. We have

$$(X \times \mathbb{P}^1)_{0,n(d,1)}^{op} \cong X \times \mathbb{C}$$

and the $\mathbb{C}^\times$-fixed locus here is a copy of $X$. The virtual fundamental class on $X$ determined by the $\mathbb{C}^\times$-fixed part of the perfect obstruction theory is the usual fundamental class of $X$. The restriction to the fixed locus of the dual to the universal cotangent line bundle $L_1$ is the trivial bundle $C_{(-1)}$ over $X$ of $\mathbb{C}^\times$-weight $-1$, and the virtual normal bundle is also $C_{(-1)}$. Thus

$$\text{(13)} \quad (\text{ev}_\infty)_* \left[ (-z) \cdot \text{ev}_1^* \mathbf{t}(\psi_1) \right] = \mathbf{t}(z).$$

Case 3: $(n,d) = (0,0)$. Here

$$(X \times \mathbb{P}^1)_{0,0(0,1)}^{op} \cong X$$

and there is no moving part of the obstruction theory. The virtual fundamental class induced on the fixed locus $X$ is the usual fundamental class of $X$, and

$$\text{(14)} \quad (\text{ev}_\infty)_* \left[ -z \right] = -z.$$
Combining (12), (13), and (14), we find that the image of the class from Theorem 1 under $\text{Ev}_\infty$ is

$$-z + t(z) + \sum_{d \in H_2(X;\mathbb{Z})_{n \geq 0}} \frac{Q^d}{n!} (\text{ev}_{n+1})_* \left[ [X_{0,n+1,d}]_{\text{vir}} \cap \prod_{i=1}^{i=n} \text{ev}_i^* t(\psi_i) \right] \cdot \frac{1}{-z - \psi_{n+1}}.$$  

This coincides with our expression (8) for a general point of $\mathcal{L}$. The proof is complete. □

**Remark 1.** We see from the proof of Theorem 1 that one should regard the factor of $-z$ occurring in the statement as the $\mathbb{C}^\times$-equivariant Euler class of $R^*\pi_* \text{ev}_{n+1}^* \mathbb{C}_{(-1)}$, where $\pi : X_{g,n+1,d} \to X_{g,n,d}$ is the universal family over the moduli space of stable maps and $\mathbb{C}_{(-1)}$ is the trivial bundle of $\mathbb{C}^\times$-weight $-1$ over $X$. Such a “twist by the Euler class” roughly corresponds to considering the Gromov–Witten theory of a hypersurface [7]. If we regard our study of $(X \times \mathbb{P}^1)_{0,n(d,1)}$ as a proxy for studying the Gromov–Witten theory of $X \times \mathbb{C}$ then the two ingredients of our construction push in opposite directions: we end up, roughly speaking, thinking of $X$ as an “equivariant hypersurface” in $X \times \mathbb{C}$, and stability as a map to $X$ and stability as a graph in $X \times \mathbb{C}$.

**Remark 2.** Our construction of $\mathcal{L}$ bears a striking resemblance to the “fundamental Floer cycle” — the semi-infinite cycle in loop space consisting of loops which bound holomorphic discs — in the heuristic picture relating quantum cohomology to the $S^1$-equivariant Floer homology of loop space outlined in [13]. This suggests that one should regard $\mathcal{H}$ as the $S^1$-equivariant Floer homology of the loop space of $X$. Other evidence for this comes from comparing the symplectic transformation in [7, Theorem 1] with the calculations in [13, Section 4], and from the beautiful recent work of Costello [10]. As mentioned above, the graph space $(X \times \mathbb{P}^1)_{0,n(d,1)}$ plays a key role in many proofs of toric mirror symmetry [3, 19, 20, 28–32], where it links Floer-theoretic predictions to rigorous calculations in Gromov–Witten theory. It would be interesting to understand exactly how $S^1$-equivariant Floer homology relates to our picture.

**Appendix: $\mathbb{C}^\times$-equivariant Borel–Moore Homology**

In [4] Braverman used a sheaf-theoretic definition of equivariant Borel–Moore homology, in the spirit of [33]. We will take a different point of view, regarding Borel–Moore homology as the homology theory of singular chains with locally finite support. This meshes more readily with constructions of the virtual fundamental class. We collect the properties of non-equivariant Borel–Moore homology that we will need in section A1 and describe the equivariant theory, constructed by Edidin and Graham in [12], in section A2. In section A3 we discuss the Borel–Moore homology of certain quotient stacks. Since the precise form of the localization theorem for $\mathbb{C}^\times$-equivariant Borel–Moore homology which we used in section 3.1 does not appear to have been written down anywhere, we prove it in section A4; it was undoubtedly already well-known.
A1. **Borel–Moore homology.** Good introductions to Borel–Moore homology can be found in [13, chapter 19], [14, Appendix B], [6, section 2.6], and [40, Appendix C]. We work with the definition from [15]: if a space \( X \) is embedded as a closed subspace of \( \mathbb{R}^n \) then
\[
H_i,BM(X) := H^{n-i}(\mathbb{R}^n, \mathbb{R}^n - X).
\]
All homology and cohomology groups are taken with complex coefficients throughout. Properties of Borel–Moore homology include:

**BM1** There are *cap products*
\[
H^j(X) \otimes H_{k,BM}(X) \to H_{k-j,BM}(X).
\]
See [15, section 19.1].

**BM2** If \( X \) is a smooth variety of dimension \( n \) then \( H_{2n,BM}(X) \) is freely generated by the fundamental class \([X] \in H_{2n,BM}(X)\), and
\[
[X] \cap : H^k(X) \to H_{2n-k,BM}(X)
\]
is an isomorphism. This is Poincaré duality. See [15, section 19.1].

**BM3** There is a Künneth formula
\[
H_{k,BM}(X \times Y) = \bigoplus_{i+j=k} H_{i,BM}(X) \otimes H_{j,BM}(Y).
\]
This follows immediately from definition (15) and the Künneth formula for relative homology.

**BM4** There are *covariant push-forwards* for proper maps \( f : X \to Y \),
\[
f_* : H_{k,BM}(X) \to H_{k,BM}(Y).
\]
See [15, section 19.1].

**BM5** There are *contravariant pull-backs* for open embeddings \( j : U \to Y \),
\[
j^* : H_{k,BM}(Y) \to H_{k,BM}(U).
\]
See [15, section 19.1].

**BM6** There is a *long exact sequence*
\[
\ldots \to H_{i+1,BM}(U) \to H_{i,BM}(X) \xrightarrow{j_*} H_{i,BM}(Y) \xrightarrow{i^*} H_{i,BM}(U) \to \ldots
\]
where \( j : U \to Y \) is an open embedding and \( i : X \to Y \) is the closed embedding of the complement \( X \) to \( U \) in \( Y \). See [15, section 19.1].

**BM7** If \( X \) is a scheme of dimension \( n \) then \( H_{i,BM}(X) = 0 \) for \( i > 2n \). This is part of Lemma 19.1.1 in [15].

**BM8** For any scheme \( X \) there is a *cycle map*
\[
cl : A_k(X) \to H_{2k,BM}(X)
\]
which is covariant for proper maps and compatible with Chern classes. See [15, section 19.1].

**BM9** For any l.c.i. morphism of schemes \( f : Y \to X \) of relative dimension \( d \) there is a *Gysin map*
\[
f^* : H_{k,BM}(X) \to H_{k-2d,BM}(Y).
\]
Such maps are functorial and compatible with the cycle class. When \( Y \) is a vector bundle over \( X \) of rank \( d \), \( f^* \) is the *Thom isomorphism* \( H_{k,BM}(X) \to H_{k+2d,BM}(Y) \). See [15, Example 19.2.1].
A2. Equivariant Borel–Moore homology. Given a $g$-dimensional linear algebraic group $G$ acting in a reasonable way on a scheme $X$ of dimension $n$, Edidin and Graham define the $G$-equivariant Borel–Moore homology groups of $X$ as

$$H^G_{i,BM}(X) := H_{i+2l_1-2g,BM}(X_G).$$

Here $X_G$ is the mixed space $(X \times U)/G$, where $U$ is an open set in an $l$-dimensional representation $V$ of $G$ such that the action of $G$ on $U$ is free and the real codimension of $V - U$ in $V$ is more than $2n - i + 1$.

One can see that this is well-defined using Bogomolov’s double filtration argument [12, Definition-Proposition 1 and Section 2.8]. Suppose that $V_1$ and $V_2$ are representations of $G$ respectively of dimensions $l_1$ and $l_2$ and containing open sets $U_1$ and $U_2$ such that the $G$-action on each $U_j$ is free and the real codimension of $V_j - U_j$ in $V_j$ is more than $2n - i + 1$. Then $V_1 \oplus V_2$ contains an open set $W$ on which $G$ acts freely and which contains both $U_1 \oplus V_2$ and $V_1 \oplus U_2$. The dimension of $$(X \times W)/G - (X \times (U_1 \oplus V_2))/G$$
is less than $2l_1 + 2l_2 - 2g + i - 1$, so

$$H_{i+2l_1+2l_2-2g,BM}(X \times W)/G = H_{i+2l_1+2l_2-2g,BM}(X \times (U_1 \oplus V_2))/G$$

by (BM6) and (BM7). But $(X \times (U_1 \oplus V_2))/G$ is a vector bundle of rank $l_2$ over $(X \times U_1)/G$, so

$$H_{i+2l_1+2l_2-2g,BM}(X \times W)/G = H_{i+2l_2-2g,BM}(X \times U_1)/G$$

by (BM9).

If the real codimension of the open set $U$ in the representation $V$ is $c$ then $\pi_j(U) = 0$ for $j < c - 1$, so the mixed spaces $X_G$ are algebraic approximations to the Borel space $(X \times EG)/G$. Combining the discussion above with the discussion in section A1 immediately yields the following properties:

EBM1 There are cap products

$$H^j_G(X) \otimes H^G_{k,BM}(X) \to H^G_{k-j,BM}(X).$$

EBM2 If $X$ is a smooth variety of dimension $n$ then there is a Poincaré duality isomorphism

$$H^G_n(X) \to H^G_{2n-k,BM}(X).$$

---

6We sidestep a technical issue here. Edidin and Graham work with algebraic spaces, rather than schemes. This is because the quotient of an algebraic space by a free action of an algebraic group is an algebraic space, but the quotient of a scheme by a free action of an algebraic group need not be a scheme. We would like the mixed space $X_G$ to be a scheme, because we want to use properties of the Borel–Moore homology of schemes listed in section A1. Proposition 23 in [12] gives conditions on the group action sufficient to ensure that $X_G$ is a scheme; we will consider only actions of $G$ on $X$ which satisfy these hypotheses, calling such actions reasonable. In view of the construction of the moduli space of stable maps as a stack quotient given in [16], it suffices for the purposes of this paper to consider only reasonable actions. Another, perhaps more satisfactory, approach would be to develop a Borel–Moore homology theory for algebraic spaces — much as is done for intersection theory in section 6.1 of [16] — but as we do not need to do this, we won’t.

7This is entirely parallel to section 2.3 of [12].
If the action of $G$ on $X$ is trivial then
\[ H^G_{k,BM}(X) = \bigoplus_{i+j=k} H_{i,BM}(X) \otimes H^G_{j,BM}(pt). \]

There are covariant push-forwards for proper $G$-equivariant maps $f : X \to Y$,
\[ f_* : H^G_{k,BM}(X) \to H^G_{k,BM}(Y). \]

There are contravariant pull-backs for $G$-equivariant open embeddings $j : U \to Y$,
\[ j^* : H^G_{k,BM}(Y) \to H^G_{k,BM}(U). \]

There is a long exact sequence
\[ \ldots \to H^G_{i+1,BM}(U) \to H^G_{i,BM}(X) \xrightarrow{j_*} H^G_{i,BM}(Y) \xrightarrow{i^*} H^G_{i,BM}(U) \to \ldots \]
where $j : U \to Y$ is a $G$-equivariant open embedding and $i : X \to Y$ is the $G$-equivariant closed embedding of the complement $X$ to $U$ in $Y$.

We have $H^G_{i,BM}(X) = 0$ for $i > 2n$.

There is a cycle map
\[ \text{cl} : A^G_0(X) \to H^G_{2k,BM}(X) \]
which is covariant for proper maps and compatible with $G$-equivariant Chern classes.

There are Gysin maps
\[ f^* : H^G_{k,BM}(X) \to H^G_{k-2d,BM}(Y) \]
for $G$-equivariant l.c.i. morphisms $f : Y \to X$ of relative dimension $d$.
These are functorial and compatible with the cycle class. When $Y$ is a $G$-equivariant vector bundle over $X$ of rank $d$, $f^*$ is the Thom isomorphism
\[ H^G_{k,BM}(X) \to H^G_{k+2d,BM}(Y). \]

**Borel–Moore homology groups for quotient stacks.** In this section, we define ordinary and $\mathbb{C}^\times$-equivariant Borel–Moore homology groups for certain quotient stacks, following [12, section 5] and [25, Appendix C]. This allows us to consider the $\mathbb{C}^\times$-equivariant Borel–Moore homology of moduli spaces of stable maps.

**Non-equivariant Borel–Moore homology.** Given a quotient stack of the form $[X/G]$, where $X$ is a scheme with a reasonable action of the $g$-dimensional linear algebraic group $G$, we define the Borel–Moore homology groups of $[X/G]$ to be
\[ H_{i,BM}([X/G]) := H^G_{i-2g,BM}(X). \]

We can see that this is well-defined using the argument of [12, Proposition 16]. Suppose that $[X/G] \cong [Y/H]$ as quotient stacks, where $G$ (respectively $H$) acts reasonably on the scheme $X$ (respectively $Y$). Let $V_1$ be an $l_1$-dimensional representation of $G$ containing an open set $U_1$ on which the $G$-action is free, and let $X_G = (X \times U_1)/G$. Let $V_2$ be an $l_2$-dimensional representation of $H$ containing an open set $U_2$ on which the $H$-action is free, and let $Y_H = (Y \times U_2)/H$. The diagonal of a quotient stack is representable, so the fiber product
\[ Z = X_G \times_{[X/G]} Y_H \]
is a scheme. But \( Z \) fibers over \( X_G \) with fiber \( U_2 \) and over \( Y_H \) with fiber \( U_1 \), so

\[
H_{i+2l_1,BM}(X_G) = H_{i+2l_1+2l_2,BM}(Z) = H_{i+2l_2,BM}(Y_H).
\]

\( \mathbb{C}^\times \)-equivariant Borel–Moore homology. Here we follow Appendix C of [25]. We define the \( \mathbb{C}^\times \)-equivariant Borel–Moore homology groups of a quotient stack \( X \) by setting

(16)

\[
H_{i,BM}^{\mathbb{C}^\times}(X) := H_{i-2l_2,BM}([(X \times U)/\mathbb{C}^\times])
\]

where \( U \) is an open set in an \( l \)-dimensional representation of \( \mathbb{C}^\times \) as above. In other words, we follow the prescription described in section A2 but construct the mixed space \( X_{\mathbb{C}^\times} \) as a stack quotient. In the case where \( X \) is the quotient of a scheme \( Y \) by a reasonable and proper action of a linear algebraic group \( G \) such that the \( \mathbb{C}^\times \)-action on \( X \) descends from a reasonable action of \( G \times \mathbb{C}^\times \) on \( Y \), we can use the constructions described earlier in this section to define the right-hand side of (16).

In applications to moduli stacks of stable maps, we need only consider quotients of this form where \( G = PGL \).

A4. Localization in \( \mathbb{C}^\times \)-equivariant Borel–Moore homology. This section contains the proof of the localization theorem which we used in section 3.1. In summary: the argument given by Graber and Pandharipande in Appendix C of [25] works for Borel–Moore homology too.

**Theorem.** Suppose that the stack \( X \) is the quotient of a scheme \( Y \) by a reasonable and proper action of a connected reductive group \( G \), and that \( X \) is equipped with a \( \mathbb{C}^\times \)-action which descends from a reasonable action of \( G \times \mathbb{C}^\times \) on \( Y \). Then the push-forward

\[
i_* : H_{*,BM}^{\mathbb{C}^\times}(X_{\mathbb{C}^\times}) \to H_{*,BM}^{\mathbb{C}^\times}(X)
\]

along the inclusion \( i : X_{\mathbb{C}^\times} \to X \) of the \( \mathbb{C}^\times \)-fixed stack becomes an isomorphism after tensoring with the field of fractions \( \mathbb{C}(z) \) of \( H^\bullet_{ST}(pt) \).

**Proof.** In view of (EBM6) if suffices to show that the \( \mathbb{C}^\times \)-equivariant Borel–Moore homology groups of \( X \) vanish after localization. But \( \mathbb{C}^\times \) acts without fixed points on \( X_{\mathbb{C}^\times} \), so \( X_{\mathbb{C}^\times} \) is the quotient of a scheme \( Z \) by a reasonable and proper action of \( G \times \mathbb{C}^\times \) and

\[
H_{i,BM}^{\mathbb{C}^\times}(X_{\mathbb{C}^\times}) = H_{i,BM}([Z/(G \times \mathbb{C}^\times)]).
\]

But these groups are non-zero in only finitely many degrees, since they are isomorphic to Borel–Moore homology groups of the coarse quotient. They therefore vanish after localization.

\[\square\]

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