SPECIAL GEOMETRY ON CALABI–YAU MODULI SPACES
AND Q-INARIANT MILNOR RINGS

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Abstract

The moduli spaces of Calabi–Yau (CY) manifolds are the special Kähler manifolds. The special Kähler geometry determines the low-energy effective theory which arises in Superstring theory after the compactification on a CY manifold. For the cases, where the CY manifold is given as a hypersurface in the weighted projective space, a new procedure for computing the Kähler potential of the moduli space has been proposed by Konstantin Aleshkin and myself. The method is based on the fact that the moduli space of CY manifolds is a marginal subspace of the Frobenius manifold which arises on the deformation space of the corresponding Landau–Ginzburg superpotential. I review this approach and demonstrate its efficiency by computing the Special geometry of the 101-dimensional moduli space of the quintic threefold around the orbifold point.

1 Introduction

To compute the low-energy Lagrangian of the string theory compactified on a CY manifold Candelas, Horowitz, Strominger, and Witten [1985], one needs to know the Special geometry of the corresponding CY moduli space Candelas, Green, and Hübsch [1989], Strominger [1990], Candelas, Green, and Hübsch [1990], and Candelas and de la Ossa [1991].

More precisely, the effective Lagrangian of the vector multiplets in the superspace contains $h^{2,1}$ supermultiplets. Scalars from these multiplets take value in the target space $\mathcal{M}$, which is a moduli space of complex structures on a CY manifold and is a special Kähler manifold. Metric $G_{ab}$ and Yukawa couplings $\kappa_{abc}$ on this space are given by the following

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formulae in the special coordinates $z^a$:

$$G_{ab} = \partial_a \partial_b K, \quad e^{-K} = -i \int_X \Omega \wedge \bar{\Omega},$$

$$\kappa_{abc} = \int_X \Omega \wedge \partial_a \partial_b \partial_c \Omega = \frac{\partial^3 F}{\partial z^a \partial z^b \partial z^c},$$

where

$$z^a = \int_{A_a} \Omega, \quad \frac{\partial F}{\partial z^a} = \int_{B^a} \Omega$$

are the period integrals of the holomorphic volume form $\Omega$ on $X$. Here $A_a$ and $B^a$ form the symplectic basis in $H_3(X, \mathbb{Z})$.

We can rewrite the expression (1) for the Kähler potential using the periods as

$$e^{-K} = -i \Pi \Sigma \Pi^\dagger, \quad \Pi = (\partial F, z),$$

where matrix $(\Sigma)^{-1}$ is an intersection matrix of cycles $A_a$, $B^a$ equal to the symplectic unit.

The computation of periods in the symplectic basis appears to be very non-trivial. It was firstly performed for the case of the quintic CY manifold in the distinguished paper Candelas, de la Ossa, Green, and Parkes [1991]. Here I present an alternative approach to the computation of Kähler potential for the case where CY manifold is given by a hypersurface $W(x, \phi) = 0$ in a weighted projective space. The approach is based on the connection of CY manifold with a Frobenius ring which arises on the deformations of the singularity defined by the superpotential $W_0(x)$ Lerche, Vafa, and N. P. Warner [1989], Martinec [1989], and Vafa and N. Warner [1989].

Let a CY manifold $X$ be given as a solution of an equation

$$W(x, \phi) = W_0(x) + \sum_{s=1}^{h^{2,1}} \phi_s e_s(x) = 0$$

in some weighted projective space, where $W_0(x)$ is a quasihomogeneous function in $\mathbb{C}^5$ of degree $d$ that defines an isolated singularity at $x = 0$. The monomials $e_s(x)$ also have degree $d$ and are in a correspondence to deformations of the complex structure of $X$.

Polynomial $W_0(x)$ defines a Milnor ring $R_0$. Inside $R_0$ there exists a subring $R_0^Q$ which is invariant under the action of the so-called quantum symmetry group $Q$ that acts on $\mathbb{C}^5$ diagonally, and preserves $W(x, \phi)$. In many cases $\dim R_0^Q = \dim H_3(X)$ and the ring
itself has a Hodge structure $R_0^Q = (R_0^Q)^0 \oplus (R_0^Q)^1 \oplus (R_0^Q)^2 \oplus (R_0^Q)^3$ in correspondence with the elements of degrees $0, d, 2d, 3d$.

Another important group is the subgroup of phase symmetries $G$, which acts diagonally on $\mathbb{C}^5$, commutes with the quantum symmetry $Q$ and preserves $W_0(x)$. It acts naturally on the invariant ring $R_0^Q$, and this action respects the Hodge decomposition of $R_0^Q$. This allows to choose a basis $e_\mu(x)$ in each of the Hodge decomposition components of $R_0^Q$ to be eigenvectors for the $G$ group action.

On the ring $R_0^Q$ we introduce the invariant pairing $\eta$. The pairing turns the ring to a Frobenius algebra Dubrovin [1992]. The pairing $\eta$ plays an important for our construction of the explicit expression for the volume of the Calabi-Yau manifold.

Using the invariant ring $R_0^Q$ and differentials $D_\pm = d \pm dW_0 \wedge$ we construct two $Q$–invariant cohomology groups $H^5_{D_\pm}(\mathbb{C}^5)_{inv}$. These groups inherit the Hodge structure from $R_0^Q$. We can choose in $H^5_{D_\pm}(\mathbb{C}^5)_{inv}$ the eigenbasises $e_\mu(x)$ $d^5x$ which are also invariant under the phase symmetry action.

As shown in Candelas [1988], elements of these cohomology groups are in correspondence with the harmonic forms of $H^3(X)$. This isomorphism allows to define the antilinear involution $*$ on the invariant cohomology $H^5_{D_\pm}(\mathbb{C}^5)_{inv}$ that corresponds to the complex conjugation on the space of the harmonic forms of $H^3(X)$.

It turns out, that in the basis $e_\mu(x)$ it reads

$$ e_\mu^*(x) d^5x = M_\mu^v e_v(x) d^5x, \quad M_\mu^v = \delta_{e_\mu,e_v} A^\mu $$

where $e_\rho(x)$ is the unique element of degree $3d$ in $R_0^Q$, and $\delta_{e_\mu,e_v} e_\rho$ is 1 if $e_\mu \cdot e_v = e_\rho$ and 0 otherwise.

Having $H^5_{D_\pm}(\mathbb{C}^5)_{inv}$ we define the relative invariant homology subgroups $\mathcal{H}^5_{D_\pm,inv} := H^5(\mathbb{C}^5, W_0 = L, \Re L \rightarrow \pm \infty)_{inv}$ inside the relative homology groups $H^5(\mathbb{C}^5, W_0 = L, \Re L \rightarrow \pm \infty)$. To do this we will use the oscillatory integrals and their pairing with elements of $H^5_{D_\pm}(\mathbb{C}^5)_{inv}$. Using this pairing we define a cycle $\Gamma^\mu_\mu$ in the basis of relative invariant homology to be dual to $e_\mu(x)$ $d^5x$.

At last we define periods $\sigma^\pm_\mu(\phi)$ to be oscillatory integrals over the basis of cycles $\Gamma^\mu_\mu$. They are equal to periods of the holomorphic volume form $\Omega$ on $X$ in a special basis of cycles of $H^3(X, \mathbb{C})$ with complex coefficients.

It follows from the phase symmetry invariance that in the chosen basis of cycles $\Gamma^\mu_\mu$ the formula for Kähler potential has the diagonal form:

$$ e^{-K(\phi)} = \sum_\mu (-1)^{|v|} \sigma^+_\mu(\phi) A^\mu \sigma^-_\mu(\phi). $$
On the other hand, as shown in Aleshkin and A. Belavin [n.d.(a)], matrix \( A = \text{diag}\{ A^\mu \} \) is equal to the product of the matrix of the invariant pairing \( \eta \) in the Frobenius algebra \( R_0^Q \) and the real structure matrix \( M \) such that

\[
e^{-K(\phi)} = \sum_{\mu, \nu} \sigma_\mu^+(\phi) \eta^{\mu \lambda} M^\nu_\lambda \overline{\sigma_\mu^-(\phi)}.
\]

The real structure matrix is nothing but matrix \( M \) from (1). Using this we are able to explicitly compute the diagonal matrix elements \( A^\mu \) and to obtain the explicit expression for the whole \( e^{-K} \).

2 The special geometry on the CY moduli space

It was shown in in Strominger [1990], Candelas, Green, and Hübsch [1989, 1990], and Candelas and de la Ossa [1991] that the moduli space \( \mathcal{M} \) of complex (or Kähler) structures of a given CY manifold is a special Kähler manifold. Namely on \( \mathcal{M} \) there exist so-called special (projective) coordinates \( z^1 \cdots z^{n+1} \) and a holomorphic homogeneous function \( F(z) \) of degree 2 in \( z \), called a prepotential, such that the Kähler potential \( K(z) \) of the moduli space metric is given by

\[
e^{-K(z)} = \int_X \Omega \wedge \overline{\Omega} = z^a \cdot \frac{\partial F}{\partial \bar{z}^a} - \bar{z}^a \cdot \frac{\partial F}{\partial z^a}.
\]

To obtain this formula, we choose Poincare dual symplectic basises \( \alpha_a, \beta^b \in H^3(X, \mathbb{Z}) \) and \( A^a, B_b \in H_3(X, \mathbb{Z}) \) and define the periods as

\[
z^a = \int_{A^a} \Omega, \quad F_b = \int_{B_b} \Omega.
\]

Then using the Kodaira Lemma

\[
\partial_a \Omega = k_a \Omega + \chi_a,
\]

we can show that

\[
F_a(z) = \frac{1}{2} \partial_a (F(z)),
\]

where \( F(z) = 1/2 z^b F_b(z) \).
Therefore, according to the definition (2) metric \(G_{a\overline{b}} = \partial_a \overline{\partial}_{\overline{b}} K(z)\) is a special Kähler metric with prepotential \(F(z)\) and with the special coordinates given by the period vector

\[ \Pi = (F_a, z^b) \]

we write the expression for the Kähler potential as

\[ e^{-K(z)} = \Pi_\mu \Sigma^{\mu\nu} \overline{\Pi}_\nu, \]

where \(\Sigma\) is a symplectic unit, which is an inverse intersection matrix for cycles \(A^a\) and \(B_b\).

Using formula (2), we can rewrite this expression in a basis of periods defined as integrals over arbitrary basis of cycles \(q_\mu \in \text{H}_3(X, \mathbb{Z})\)

\[ \omega_\mu = \int_{q_\mu} \Omega. \]

Such that

\[ e^{-K} = \omega_\mu C^{\mu\nu} \overline{\omega}_\nu, \]

where \(C^{\mu\nu}\) is the inverse matrix of the intersection of the cycles \(q_\mu\).

So to find the Kähler potential, we must compute the periods over a basis of cycles on CY manifold and find their intersection matrix.

### 3 Hodge structure on the middle cohomology of the quintic

Now let us specialize to the case where \(X\) is a quintic threefold:

\[ X = \{ (x_1 : \cdots : x_5) \in \mathbb{P}^4 \mid W(x, \phi) = 0 \}, \]

and

\[ W(x, \phi) = W_0(x) + \sum_{t=0}^{100} \phi_t e_t(x), \quad W_0(x) = x_1^5 + x_2^5 + x_3^5 + x_4^5 + x_5^5 \]

and \(e_t(x)\) are the degree 5 monomials such that each variable has the power that is a non-negative integer less than four. Let us denote monomials \(e_t(x) = x_1^{t_1} x_2^{t_2} x_3^{t_3} x_4^{t_4} x_5^{t_5}\) by its
degree vector \( t = (t_1, \ldots, t_5) \). Then there are precisely 101 of such monomials, which can be divided into 5 sets in respect to the permutation group \( S_5 \): \((1, 1, 1, 1, 1), (2, 1, 1, 1, 0), (2, 2, 1, 0, 0), (3, 1, 1, 0, 0), (3, 2, 0, 0, 0)\). In these groups there are correspondingly 1, 20, 30, 30, 20 different monomials. We denote \( e_0(x) := e_{(1,1,1,1,1)}(x) = x_1x_2x_3x_4x_5 \) to be the so-called fundamental monomial, which will be somewhat distinguished in our picture.

For this CY \( \dim H_3(X) = 204 \) and period integrals have the form

\[
\omega_\mu(x) = \int_q \frac{x_5 \, dx_1 \, dx_2 \, dx_3}{\partial W(x, \phi)/\partial x_4} = \int_{Q_\mu} \frac{dx_1 \cdots dx_5}{W(x, \phi)},
\]

where \( q_\mu \in H_3(X, \mathbb{Z}) \) and the corresponding cycles \( Q_\mu \in H_3(C^5 \setminus (W(x, \phi) = 0), \mathbb{Z}) \).

Cohomology groups of the Kähler manifold \( X \) possess a Hodge structure \( H^3(X) = H^{3,0}(X) \oplus H^{1,2}(X) \oplus H^{2,1}(X) \oplus H^{0,3}(X) \). Period integrals measure variation of the Hodge structure on \( H^3(X) \) as the complex structure on \( X \) varies with \( \phi \).

This Hodge structure variation is in correspondence with a Frobenius ring which we will now describe.

### 4 Hodge structure on the invariant Milnor ring

Now we will consider \( W_0(x) \) as an isolated singularity in \( C^5 \) and the associated with it Milnor ring

\[
R_0 = \frac{\mathbb{C}[x_1, \ldots, x_5]}{\langle \partial_i W_0 \rangle}.
\]

We can choose its elements to be unique smallest degree polynomial representatives. For the quintic threefold \( X \) its Milnor ring \( R_0 \) is generated as a vector space by monomials where each variable has degree less than four, and \( \dim R_0 = 1024 \).

Since the polynomial \( W_0(x) \) is homogeneous one of the fifth degree it follows that \( W_0(\alpha x_1, \ldots, \alpha x_5) = W_0(x_1, \ldots, x_5) \) for \( \alpha^5 = 1 \). This action preserves \( W_0(x) \) and is trivial in the corresponding projective space and on \( X \). Such a group with this action is called a quantum symmetry \( Q \), in our case \( Q \simeq \mathbb{Z}_5 \). \( Q \) obviously acts on the Milnor ring \( R_0 \).

We define a subring \( R_0^Q \) to be a \( Q \)-invariant part of the Milnor ring

\[
R_0^Q := \{ e_\mu(x) \in R_0 | e_\mu(\alpha x) = e_\mu(x) \}, \alpha^5 = 1.
\]
$R_0^Q$ is multiplicatively generated by 101 fifth-degree monomials $e_t(x)$ from (3) and consists of elements of degree 0, 5, 10 and 15. The dimensions of the corresponding subspaces are 1, 101, 101 and 1.

This degree filtration defines a Hodge structure on $R_0^Q$. Actually, $R_0^Q$ is isomorphic to $H^{3}(X)$ and this isomorphism sends the degree filtration on $R_0^Q$ to the Hodge filtration on $H^{3}(X)$ Candelas [1988].

Let us denote $\chi^i_j = g^{ik} \chi_k j$ as an extrinsic curvature tensor and $g_{i\bar{k}}$ is a metric for the hypersurface $W(x, \phi) = 0$ in $\mathbb{P}^4$. Then the isomorphism above can be written as a map from $R_0^Q$ to closed differential forms in $H^{3}(X)$:

$$1 \to \Omega_{ijk} \in H^{3,0}(X),$$

$$e_{\mu}(x) \to e_{\mu}(x(y)) \chi^i_j \Omega_{ijk} \in H^{2,1}(X) \text{ if } |\mu| = 5,$$

$$e_{\mu}(x) \to e_{\mu}(x(y)) \chi^i_j \chi^m_l \Omega_{lmk} \in H^{1,2}(X) \text{ if } |\mu| = 10,$$

$$e_{\rho}(x) = x_1^5 x_2^5 x_3^5 x_4^5 x_5^5 \to \chi^i_j \chi^m_l \chi^p_n \Omega_{lmn} = \kappa \Omega \in H^{0,3}(X)$$

The details of this map can be found in Candelas [ibid.]. We also introduce the notation $e_{\mu}(x)$ for elements of the monomial basis of $R_0^Q$, where $\mu = (\mu_1, \cdots, \mu_5), \mu_i \in \mathbb{Z}_+^5, e_{\mu}(x) = \prod_i x_i^{\mu_i}$ and the degree of $e_{\mu}(x)$ $\mu = \sum \mu_i$ is equal to zero module 5. In particular, $\rho = (3, 3, 3, 3, 3)$, that is $e_{\rho}(x)$ is the unique degree 15 element of $R_0^Q$.

The phase symmetry group $\mathbb{Z}_5^5$ acts diagonally on $\mathbb{C}^5$: $\alpha \cdot (x_1, \cdots, x_5) = (\alpha_1 x_1, \cdots, \alpha_5 x_5), \alpha_5^5 = 1$. This action preserves $W_0 = \sum_i x_i^5$. The mentioned above quantum symmetry $Q$ is a diagonal subgroup of the phase symmetries. Basis $\{e_{\mu}(x)\}$ consists of the eigenvectors of the phase symmetry and each $e_{\mu}(x)$ has a unique weight. Note that the action of the phase symmetry preserves the Hodge decomposition.

Another important fact is that on the invariant ring $R_0^Q$ there exists a natural invariant pairing turning it into a Frobenius algebra Dubrovin [1992]:

$$\eta_{\mu \nu} = \text{Res} \frac{e_{\mu}(x) e_{\nu}(x)}{\prod_i \partial_i W_0(x)}.$$

Up to an irrelevant constant for the monomial basis it is $\eta_{\mu \nu} = \delta_{\mu+\nu, \rho}$. This pairing plays a crucial role in our construction.

Let us introduce a couple of Saito differentials as in Aleshkin and A. Belavin [n.d.(a)] on differential forms on $\mathbb{C}^5$: $D_+ = d \pm dW_0(x) \wedge$. They define two cohomology groups $H_D^*(\mathbb{C}^5)$. The cohomologies are only nontrivial in the top dimension $H_D^5(\mathbb{C}^5) \simeq R_0$.  

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The isomorphism $J$ has an explicit description

$$J(e_\mu(x)) = e_\mu(x) \, d^5 x, \; e_\mu(x) \in R_0.$$ 

We see, that $Q = \mathbb{Z}_5$ naturally acts on $H^5_{D\pm}(C^5)$ and $J$ sends the elements of $Q$-invariant ring $R_0^Q$ to $Q$-invariant subspace $H^5_{D\pm}(C^5)_{inv}$. Therefore, the latter space obtains the Hodge structure as well. Actually, this Hodge structure naturally corresponds to the Hodge structure on $H^3(X)$.

The complex conjugation acts on $H^3(X)$ so that $\overline{H^{p,q}(X)} = H^{q,p}(X)$, in particular $H^{2,1}(X) = H^{1,2}(X)$. Through the isomorphism between $R_0^Q$ and $H^3(X)$ the complex conjugation acts also on the elements of the ring $R_0^Q$ as $\ast e_\mu(x) = p_\mu e_{\rho-\mu}(x)$, where $p_\mu p_{\rho-\mu} = 1$ and $p_\mu$ is a constant to be determined. In particular, differential form built from the linear combinations $e_\mu(x) + p_\mu e_{\rho-\mu}(x) \in H^3(X, \mathbb{R})$ is real.

5 Oscillatory representation and computation periods $\sigma_\mu(\phi)$

Relative homology groups $H_5(C^5, W_0 = L, \, \text{Re}L \to \pm \infty)$ have a natural pairing with $Q$-invariant cohomology groups $H^5_{D\pm}(C^5)_{inv}$ defined as

$$\langle e_\mu(x) d^5 x, \Gamma^{\pm} \rangle = \int_{\Gamma^{\pm}} e_\mu(x) e^{\mp W_0(x)} d^5 x, \; H_5(C^5, W_0 = L, \, \text{Re}L \to \pm \infty).$$

Using this we introduce two $Q$-invariant homology groups $\mathcal{H}_5^{\pm,inv}$ as quotient of $H_5(C^5, W_0 = L, \, \text{Re}L \to \pm \infty)$ with respect to the subgroups orthogonal to $H^5_{D\pm}(C^5)_{inv}$. Now we introduce basises $\Gamma^{\pm}_\mu$ in the homology groups $\mathcal{H}_5^{\pm,inv}$ using the duality with the basises in $H^5_{D\pm}(C^5)_{inv}$:

$$\int_{\Gamma^{\pm}_\mu} e_{\nu}(x) e^{\mp W_0(x)} d^5 x = \delta_{\mu \nu}$$

and the corresponding periods

$$\sigma^{\pm}_\alpha(\phi) := \int_{\Gamma^{\pm}_\mu} e_{\alpha}(x) e^{\mp W(x, \phi)} d^5 x, \quad \sigma^{\pm}_\mu(\phi) := \sigma^{\pm}_0(\phi)$$

$^1$We are grateful to V. Vasiliev for explaining to us the details about these homology groups and their connection with the middle homology of $X$. 

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which are understood as series expansions in $\phi$ around zero.

The periods $\sigma_{\mu}^{\pm}(\phi)$ satisfy the same differential equation as periods $\omega_{\mu}(\phi)$ of the holomorphic volume form on $X$. Moreover, these sets of periods span same subspaces as functions of $\phi$. Therefore we can define cycles $Q_{\mu}^{\pm} \in \mathcal{H}^{5,inv}_{\pm}$ such that

$$
\int_{Q_{\mu}^{\pm}} e^{\mp W(x,\phi)} d^{5}x = \int_{q_{\mu}} \Omega = \int_{Q_{\mu}} \frac{d^{5}x}{W(x,\phi)}.
$$

So the periods $\omega_{\alpha\mu}^{\pm}(\phi)$ are given by the integrals over these cycles analogous to (5).

With these notations the idea of computation of periods A. Belavin and V. Belavin [2016]

$$\sigma_{\mu}^{\pm}(\phi) = \int_{\Gamma_{\mu}^{\pm}} e^{\mp W(x,\phi)} d^{5}x$$

can be stated as follows.

To explicitly compute $\sigma_{\mu}^{\pm}(\phi)$, first we expand the exponent in the integral (5) in $\phi$ representing $W(x,\phi) = W_{0}(x) + \sum_{s} \phi_{s} e_{s}(x)$

$$
\sigma_{\mu}^{\pm}(\phi) = \sum_{m} \left( \prod_{s} \frac{(\pm \phi_{s})^{m_{s}}}{m_{s}!} \right) \int_{\Gamma_{\mu}^{\pm}} \prod_{s} e_{s}(x)^{m_{s}} e^{\mp W_{0}(x)} d^{5}x.
$$

We note, that $\sigma_{\mu}^{-}(\phi) = (-1)^{\mu} \sigma_{\mu}^{+}(\phi)$, so we focus on $\sigma_{\mu}(\phi) := \sigma_{\mu}^{+}(\phi)$.

For each of the summands in (5) the form $\prod_{s} e_{s}(x)^{m_{s}} d^{5}x$ belongs to $H_{D_{\pm}}^{5}(\mathbb{C}^{5})_{inv}$, because it is $Q-$invariant. Therefore, we can expand it in the basis $e_{\mu}(x) d^{5}x \in H_{D_{\pm}}^{5}(\mathbb{C}^{5})_{inv}$. Namely we can find such a polynomial 4–form $U$, that

$$
\prod_{s} e_{s}(x)^{m_{s}} d^{5}x = \sum_{\nu} C_{\nu}(m) e_{\nu}(x) d^{5}x + D_{+}U.
$$

In result we obtain for the integral in (5)

$$
\int_{\Gamma_{\mu}^{\pm}} \prod_{s} e_{s}(x)^{m_{s}} e^{\mp W_{0}(x)} d^{5}x = C_{\mu}(m).
$$

So from (5) we have

$$
\sigma_{\mu}(\phi) = \sum_{m} \left( \prod_{s} \frac{\phi_{s}^{m_{s}}}{m_{s}!} \right) \int_{\Gamma_{\mu}^{+}} \prod_{s,i} x_{i}^{\sum_{s} m_{s} s_{i}} e^{-W_{0}(x)} d^{5}x.
$$
We can rewrite the sum in the exponent of \( x_i \) as \( \sum_s m_s s_i = 5n_i + v_i, \ v_i < 5 \). Therefore we need to compute the coefficients \( c_m^v \) in the equations

\[
\prod_i x_i^{5n_i + v_i} \, d^5 x = \sum_v c_v^m \, e_v(x) \, d^5 x + D_+ U.
\]

Note that

\[
D_+ \left( \frac{1}{5} x_1^{5n + k - 4} f(x_2, \ldots, x_5) \, dx_2 \wedge \cdots \wedge dx_5 \right) = \\
= \left[ x_1^{5n + k} + \left( n + \frac{k - 4}{5} \right) x_1^{5(n-1) + k} \right] f(x_2, \ldots, x_5) \, d^5 x
\]

Therefore in \( D_+ \) cohomology we have

\[
\prod_i x_i^{5n_i + v_i} \, d^5 x = - \left( n_1 + \frac{v_1 - 4}{5} \right) x_i^{5(n_i - 1) + v_1} \prod_{i=2}^5 x_i^{5n_i + v_i} \, d^5 x, \ v_i < 5.
\]

By induction we obtain

\[
\prod_i x_i^{5n_i + v_i} \, d^5 x = (-1)^{\sum_i n_i} \prod_i \left( \frac{v_i + 1}{5} \right)^{n_i} \prod_i x_i^{v_i} \, d^5 x, \ v_i < 5.
\]

where \((a)_n = \Gamma(a + n) / \Gamma(a)\).

Using (5) once again, we see that if any \( v_i = 4 \) then the differential form is trivial and the integral is zero. Hence, rhs of (5) is proportional to \( e_v(x) \) and gives the desired expression. Plugging (5) into (5) and integrating over \( \Gamma_{\mu}^+ \) we obtain the answer

\[
\sigma_\mu(\phi) = \sigma_\mu^+(\phi) = \sum_{n_i \geq 0} \prod_i \left( \frac{\mu_i + 1}{5} \right)^{n_i} \sum_{m \in \Sigma_n} \prod_s \frac{\phi_s^{m_s}}{m_s!},
\]

where

\[
\Sigma_n = \{ m \mid \sum_s m_s s_i = 5n_i + \mu_i \}\]
Further we will also use the periods with slightly different normalization, which turn out to be convenient

\[ \hat{\sigma}_\mu(\phi) = \prod_i \Gamma \left( \frac{\mu_i + 1}{5} \right) \sigma_\mu(\phi) = \sum_{n_i \geq 0} \prod_i \Gamma \left( n_i + \frac{\mu_i + 1}{5} \right) \sum_{m \in \Sigma} \prod_s \frac{\phi_s^{ms}}{m_s!}. \]

6 Computation of the Kähler potential

Pick any basis \( Q_\mu^\pm \) of cycles with integer or real coefficients as in (5). Then for the Kähler potential we have the formula

\[ e^{-K} = \omega_\mu^+(\phi) C^{\mu\nu} \omega_\nu^-(\phi) \]

in which the matrix \( C^{\mu\nu} \) is related with the Frobenius pairing \( \eta \) as

\[ \eta_{\alpha\beta} = \omega_{\alpha\mu}(0) C^{\mu\nu} \omega_{\nu\beta}(0). \]

The derivation of the last relation is given in Cecotti and Vafa [1991] and Chiodo, Iritani, and Ruan [2014].

Let also \( T^\pm \) be the matrix that connects the cycles \( Q_\mu^\pm \) and \( \Gamma_\nu^\pm \). That is

\[ Q_\mu^\pm = (T^\pm)_\mu^\nu \Gamma_\nu^\pm \]

Then \( M = (T^-)^{-1} T^- \) is a real structure matrix, that is \( M \bar{M} = 1 \) and by construction \( M \) doesn’t depend on the choice of basis \( Q_\mu^\pm \). \( M \) is only defined by our choice of \( \Gamma_\mu^\pm \).

In Aleshkin and A. Belavin [n.d.(a)] we deduced from (6) and (6) the formula

\[ e^{-K}(\phi) = \sigma_\mu^+(\phi) \eta^{\mu\lambda} M^{\nu}_\lambda \sigma_\nu^-(\phi) = \sigma_\mu A^{\mu\nu} \bar{\sigma}_\nu, \]

where \( \eta^{\mu\nu} = \eta_{\mu\nu} = \delta_{\mu,\rho-\nu} \).

Now we show that the matrix \( A^{\mu\nu} \) in (6) is diagonal. To do this we extend the action of the phase symmetry group to the action \( A \) on the parameter space \( \{ \phi_s \} \) such that \( W = W_0 + \sum_s \phi_se_s(x) \) is invariant under this new action. It easy to see that each \( e_s(x) \) has an unique weight under this group action. Action \( A \) can be compensated using the coordinate tranformation and therefore is trivial on the moduli space of the quintic (implying that point \( W = W_0 \) is an orbifold point of the moduli space).

In particular, \( e^{-K} = \int_X \Omega \wedge \bar{\Omega} \) is \( A \) invariant. Consider

\[ e^{-K} = \sigma_\mu A^{\mu\nu} \bar{\sigma}_\nu \]
as a series in $\phi_s$ and $\overline{\phi_t}$. Each monomial has a certain weight under $A$. For the series to be invariant, each monomial must have weight 0. But weight of $\sigma_\mu \sigma_v$ equals to $\mu - v$ and due to non-degeneracy of weights of $\sigma_\mu$ only the ones with $\mu = v$ have weight zero. Thus, (6) becomes

$$e^{-K} = \sum_\mu A^\mu |\sigma_\mu(\phi)|^2.$$ 

Moreover, the matrix $A$ should be real and, because $A = \eta \cdot M$, $\overline{M} \overline{M} = 1$ and $\eta_{\mu v} = \delta_{\mu + v, \rho}$, we have

$$A^\mu A^{\rho - \mu} = 1.$$ 

**Monodromy considerations.** To fix finally the real numbers $A^\mu$ we use monodromy invariance of $e^{-K}$ around $\phi_0 = \infty$. Pick some $t = (t_1, t_2, t_3, t_4, t_5)$ with $|t| = 5$ and let $\phi_s|_{s \neq t, 0} = 0$. We will consider only the first order in $\phi_t$.

Then the condition that period $\sigma_\mu(\phi)$ contains only non-zero summands of the form $\phi_0^{m_0} \phi_t$ implies that $\mu = t + \text{const} \cdot (1, 1, 1, 1, 1) \mod 5$. For each $t$ from the table below the only such possibilities are $\mu = t$ and $\mu = \rho - t' = (3, 3, 3, 3) - t'$, where $t'$ denotes a vector obtained from $t$ by permutation (written explicitly in the table below) of its coordinates.

Therefore, in this setting (6) becomes

$$e^{-K} = \sum_{k=0}^3 a_k |\hat{\sigma}(k,k,k,k,k)|^2 + a_t |\hat{\sigma}_t|^2 + a_{\rho - t'} |\hat{\sigma}_{\rho - t'}|^2 + O(\phi_t^2),$$

here we use periods $\hat{\sigma}$ from (5) and denote $a_t = A^t / \prod_1 \Gamma((t_i + 1)/5)^2$. And the coefficients $a_k, k = 0, 1, 2, 3$ are already known from Candelas, de la Ossa, Green, and Parkes [1991]. This expression has to be monodromy invariant under the transport of $\phi_0$ around $\infty$. From the formula (5) we have

$$F_1 = \hat{\sigma}_k(\phi_t, \phi_0) = g_t \phi_k F(a, b; a + b \mid (\phi_0/5)^5) + O(\phi_t^6),$$

$$F_2 = \hat{\sigma}_{\rho - t'}(\phi_t, \phi_0) = g_{\rho - t'} \phi_t \phi_0^{1-a-b} F(1 - a, 1 - b; 2 - a - b \mid (\phi_0/5)^5) + O(\phi_t^6),$$

where $g_t, g_{\rho - t'}$ are some constants. Explicitly for all different labels $t$
When $\phi_0$ goes around infinity

$$\begin{pmatrix} F_1 \\ F_2 \end{pmatrix} = B \cdot \begin{pmatrix} F_1 \\ F_2 \end{pmatrix},$$

where

$$B = \frac{1}{i s(a+b)} \left( c(a-b) - e^{i\pi(a+b)} ight) \left( 2e^{2i\pi(a+b)}s(a)s(b) \right) \frac{2s(a)s(b)}{2i e^{2\pi i a} + 2e^{2\pi i b} - 2}. $$

Here $c(x) = \cos(\pi x)$, $s(x) = \sin(\pi x)$. It is straightforward to show the following

**Proposition 1.**

$$a_t |\hat{\sigma}_t|^2 + a_{t-t'}|\hat{\sigma}_{t-t'}|^2 = a_t \prod_i \Gamma \left( \frac{t_i + 1}{5} \right)^2 |\sigma_t|^2 + a_{t-t'} \prod_i \Gamma \left( \frac{4-t_i}{5} \right)^2 |\sigma_{t-t'}|^2$$

is $B$-invariant iff $a_t = -a_{t-t'}$.

Due to symmetry we have $a_{t-t'} = a_{t-t}$ in each case. From (6) it follows that the product of the coefficients at $|\sigma\mu|^2$ and $|\sigma_{\mu-t}|^2$ in the expression for $e^{-K}$ should be 1:

$$A^{t-t'} \cdot A^t = a_{t-t'} \cdot a_t \prod_i \Gamma \left( \frac{t_i + 1}{5} \right)^2 \Gamma \left( \frac{4-t_i}{5} \right)^2 = 1.$$

Due to reflection formula $a_t = \pm \prod_i \sin(\pi(t_i + 1)/5)$ up to a common factor of $\pi$. The sign turns out to be minus for Kähler metric to be positive definite in the origin. Therefore

$$A^\mu = (-1)^{\deg(\mu)/5} \prod_i \gamma \left( \frac{\mu_i + 1}{5} \right).$$

Finally the Kähler potential becomes

$$e^{-K(\phi)} = \sum_{\mu=0}^{203} (-1)^{\deg(\mu)/5} \prod_i \gamma \left( \frac{\mu_i + 1}{5} \right) |\sigma_{\mu}(\phi)|^2,$$
where \( \gamma(x) = \frac{\Gamma(x)}{\Gamma(1-x)} \).

7 Real structure on the cycles \( \Gamma_\mu^\pm \)

Let cycles \( \gamma_\mu \in H_3(X) \) be the images of cycles \( \Gamma_\mu^+ \) under the isomorphism \( H_{5,\text{inv}}^+ \cong H_3(X) \).

Complex conjugation sends \((2, 1)\)-forms to \((1, 2)\)-forms. Similarly it extends to a mapping on the dual homology cycles \( \gamma_\mu \).

**Lemma 1.** Conjugation of homology classes has the following form: \( \star \gamma_\mu = p_\mu \gamma_{\rho-\mu} \), where \( \rho = (3, 3, 3, 3, 3) \) is a unique maximal degree element in the Milnor ring.

**Proof.** We perform a proof for the cohomology classes represented by differential forms. For one-dimensional \( H^{3,0}(X) \) and \( H^{0,3}(X) \) it is obvious. Let

\[
\Omega_{2,1} := e_t(x) \chi_{i}^l \Omega_{ljk} \in H^{2,1}(X).
\]

Any element from \( H^{1,2}(X) \) is representable by a degree 10 polynomial \( P(x) \) as follows from (4) as

\[
\overline{\Omega_{2,1}} = \Omega_{1,2} := P(x) \chi_{i}^l \chi_{j}^m \Omega_{lmk} \in H^{1,2}(X).
\]

The group of phase symmetries modulo common factor acts by isomorphisms on \( X \). Therefore, it also acts on the differential forms. Lhs and rhs of the previous equation should have the same weight under this action, and weight of the lhs is equal \(-t\) modulo \((1, 1, 1, 1, 1)\). It follows that \( P(x) = p_t e_{\rho-t}(x) \) with some constant \( p_t \).

Using this lemma and applying the complex conjugation of cycles to the formula (6) to obtain

\[
e^{-K} = \sum_\mu A^\mu |\sigma_\mu|^2 = \sum_\mu p_\mu^2 A^\mu |\sigma_{\rho-\mu}|^2,
\]

it follows that \( A^\mu = \pm 1/p_\mu \). Now formula (6) implies

\[
p_\mu = \prod \gamma \left( \frac{4 - \mu_i}{5} \right).
\]
8 Conclusion

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