Seiberg-Witten Theory and Topological Recursion

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“Every world-changing ideas started from a blank page”

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Declaration

This thesis is an account of research undertaken between February 2016 and February 2020 at The School of Mathematics and Statistics, Faculty of Science, The University of Melbourne, Melbourne, Australia.

Except where acknowledged in the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university. The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies.

Wee Chaimanowong
August 7, 2020
Chapter 1

Introduction

Since its introduction in 1994, Seiberg-Witten theory \[35\] has been an active research topic in both the physics and mathematics communities. From the physics point of view, it is an exact low-energy effective field theory of an \(N = 2\) supersymmetric \(SU(N)\) gauge theory. From the mathematical point of view, all the physical information can be encoded into an \(N\)-dimensional family \(B\) of genus \(N\) connected compact Riemann surfaces \(\Sigma\) known as Seiberg-Witten curves. Each Seiberg-Witten curve is equipped with a residueless meromorphic differential form \(dS_{SW}\) called the Seiberg-Witten differential. The homology group \(H_1(\Sigma, \mathbb{C})\) is naturally equipped with a symplectic structure, given by the oriented intersection product. By choosing symplectic basis cycles \(A\) and \(B\) for the homology group, the corresponding \(A\) and \(B\)-periods of \(dS_{SW}\) recover the electric \((a_1, \cdots, a^N)\) and magnetic \((b_1, \cdots, b_N)\) charges of the theory respectively.

The supersymmetric origin of Seiberg-Witten theory enforces that the effective action of the theory is completely determined by a holomorphic function \(\mathcal{F}^{SW} = \mathcal{F}^{SW}(\{a^i\}_{i=1}^N, \Lambda)\) known as the Seiberg-Witten prepotential. The parameter \(\Lambda\) is the energy scale of the theory where gauge couplings become strong. Therefore, technically we should have written \(B\) as \(B(\Lambda)\) to emphasize the dependency of the family on the energy scale \(\Lambda\). In the original work \[35\], the electric-magnetic duality was employed to constrain the form of the prepotential. A more mathematical approach to the computation of the prepotential has been studied via Nekrasov’s partition function a few years later by various authors \[32, 33, 31, 50\].

Nekrasov’s partition function \(Z(\{a^i\}, \{\epsilon_1, \epsilon_2\}, \Lambda)\) is the path-integral over the non-perturbative instanton contributions of a certain \((\epsilon_1, \epsilon_2)\)-deformed \(N = 2\) supersymmetric \(SU(N)\) gauge theory. It can be written as an integral over the moduli space of instantons which can be evaluated via Atiyah-Bott equivariant localization formula \[2\]. In the end, we find that \(Z(\{a^i\}, \epsilon_1, \epsilon_2, \Lambda)\) is a sum of terms indexed by \(N\)-tuples of Young’s diagrams over all possible \(N\)-tuples of Young’s diagrams with boxes of width \(-\epsilon_1\) and height \(+\epsilon_2\). In the limit \(\epsilon_1, \epsilon_2 \to 0\), Young diagrams become continuous graphs \(f\) and there exists the function \(f_0\) in which the corresponding term in the summation:

\[
\mathcal{F}_0(\{a^i\}, \Lambda) = \lim_{\epsilon_1, \epsilon_2 \to 0} \epsilon_1 \epsilon_2 \log Z(\{a^i\}, \epsilon_1, \epsilon_2, \Lambda)
\]

will dominate the contribution. It was proven by Nekrasov-Okounkov \[33, 32\] that \(\mathcal{F}_0\) is the Seiberg-Witten prepotential \(\mathcal{F}_{SW}\). The same result was independently proven using techniques in algebraic geometry by Nakajima-Yoshioka \[30, 31\].

Mathematically, the Seiberg-Witten prepotential \(\mathcal{F}_{SW}\) contains information about the deformation of Seiberg-Witten curves \(\Sigma\) in the family \(B\). A Seiberg-Witten curve \(\Sigma\) is represented by a point \([\Sigma]\) \(\in B\). Let us define the regular locus \(B^{reg}\) of \(B\) to be the dense subset of points \([\Sigma]\) \(\in B\) such that \(\Sigma\) is non-singular. The set \(\{a^1 := a^1(\Sigma), \cdots, a^N := a^N(\Sigma)\}\) where \(a^i(\Sigma) := f_{A_i \subset \Sigma} dS_{SW}\) are \(A\)-periods of the Seiberg-Witten differential on \(\Sigma\) is a system of local holomorphic coordinates on some neighbourhoods \(B_{\Sigma} \subseteq B^{reg}\) of an arbitrary point \([\Sigma] \in B^{reg}\) giving \(B^{reg}\) the structure of an \(N\)-dimensional complex manifold. Let us fix a point \([\Sigma_0] \in B^{reg}\). The prepotential \(\mathcal{F}_{SW} : B_{\Sigma_0} \to \mathbb{C}\) is a holomorphic function locally defined on some open neighbourhood \(B_{\Sigma_0} \subseteq B^{reg}\) of \([\Sigma_0]\) which relates the \(B\)-periods on \(\Sigma\) of the Seiberg-Witten differential, \(b_i(\Sigma) := f_{B_i \subset \Sigma} dS_{SW}\), to its \(A\)-periods as follows:

\[
b_i = b_i(\Sigma) = \frac{\partial \mathcal{F}_{SW}(\{a^h\}, \Lambda)}{\partial a^i}, \quad i = 1, \cdots, N, \quad [\Sigma] \in B_{\Sigma_0}.
\]

Let us explore the prepotential from another important viewpoint. Similarly to how we equipped the homology group \(H_1(\Sigma, \mathbb{C})\) with a symplectic structure, the cohomology group \(H^1(\Sigma, \mathbb{C}) \cong H_1(\Sigma, \mathbb{C})^*\) may be equipped
with a symplectic structure given by the oriented intersection of cohomological classes via Poincaré duality. We can say that the existence of prepotential $\mathfrak{F}^{SW}_{reg}$ is also equivalent to the fact that

$$L_{\Sigma}: = \{ (a^1(\Sigma), \ldots, a^N(\Sigma), b_1(\Sigma), \ldots, b_N(\Sigma)) \mid \{ \Sigma \} \in B_{\Sigma_0} \} \subset C^{2g} \cong H^1(\Sigma_0, \mathbb{C})$$

is a Lagrangian submanifold. From this point of view, the prepotential is the generating function of $L_{\Sigma}$. Here we have identified $H^1(\Sigma, \mathbb{C})$ for every $\{ \Sigma \} \in B_{\Sigma_0}$ with $C^{2g}$. Consider the symplectic vector bundle $\mathcal{H} \to B_{\Sigma_0}$ equipped with the Gauss-Manin connection $\nabla_{GM}$ and with the fiber over $\{ \Sigma \} \in B_{\Sigma_0}$ given by $\mathcal{H}_\Sigma := H^1(\Sigma, \mathbb{C})$. Then $L_{\Sigma} \subset H_{\Sigma_0} = H^1(\Sigma_0, \mathbb{C})$ is the image of the embedding of $B_{\Sigma_0}$ into the fiber $H_{\Sigma_0}$ given by sending the cohomology class of $dS_{SW}$ over $\{ \Sigma \} \in B_{\Sigma_0}$ to $\{ \Sigma \}$ via the parallel transport.

In fact, the existence of the Seiberg-Witten prepotential $\mathfrak{F}^{SW}_{reg}$ is a consequence of an important property of the Seiberg-Witten differential, namely, any infinitesimal variations of $dS_{SW}$ in the family $B$ using a certain choice of connection is a global holomorphic form on $\Sigma$. Based on this key property, we may consider a generalized notion of ‘Seiberg-Witten theory’ as follows. Let $B$ be an arbitrary $g$ dimensional family of genus $g$ curves $\Sigma$ and each $\Sigma$ is equipped with a residueless meromorphic differential $\omega$, called Symmetric meromorphic multi-differentials $\omega$ with some additional data. Topological recursion is a recursive procedure which takes a spectral curve as input and produces symmetric meromorphic multi-differentials $\omega$ with some additional data. Topological recursion was introduced by Eynard-Orantin [21, 29], instead of just a single energy scale parameter $\Lambda$, we can consider an infinite number of time variables $\{ T^{k=0,1,2,\cdots} \}$ such that $\partial_dS/\partial T^k = d\Omega_k$ for some meromorphic differentials $d\Omega_k$ on $\Sigma$. In this context, the main problem to consider is the following: given a set of meromorphic differentials $\{d\Omega_k=0,1,2,\cdots\}$ on $\Sigma$ in the family of curves $\mathcal{B}(\{ T^{k=0,1,2,\cdots} \})$, find (if possible) the meromorphic differential $dS$ on $\Sigma$ satisfying (1.1) and $\partial dS/\partial T^k = d\Omega_k$.

In this work, we consider the complex analytic moduli space $B$ of smooth compact complex genus $g$ curves $\Sigma$ embedded inside a foliated symplectic surface $S$ tangent to the leaves of the foliation $F$ at finitely many points with tangency order 1. Let us call any curve $\Sigma \in B$ a $F$-transversal curve and call points where $\Sigma$ is tangent to $F$ the ramification points of $\Sigma$. We will examine the deformation of curves in $B$, using the Kontsevich-Soibelman approach to topological recursion [25] with Seiberg-Witten family of curves as the main example.

A spectral curve is a Riemann surface $\Sigma$ with some distinct points $\{ \tau_{\alpha \in \text{Ram}} \}$ called ramification points together with some additional data. Topological recursion is a recursive procedure which takes a spectral curve as input and produces symmetric meromorphic multi-differentials $\omega_{\gamma,n}$ which are sections of $\Omega^n_{\Sigma}(\Sigma \setminus \{ \tau_{\alpha \in \text{Ram}} \})^n$. For instance, $\omega_{\gamma,1}$ is a meromorphic differential on $\Sigma$. Topological recursion was introduced by Eynard-Orantin [14, 15] around 2007-2008 with a wide variety of applications in areas ranging from mathematical physics to enumerative geometry. For example, it has been shown [14, 15] by comparing the topological recursion relations with a particular choice of the spectral curve to loop equations that the corresponding output $\omega_{\gamma,n}$ are given by the correlation functions in Matrix models. Similarly, let the spectral curve be given by an Airy curve with some additional data. It has been shown [13] that coefficients of the Laurent expansion of $\omega_{\gamma,n}$ centered at the only ramification point is related to the intersection number of divisor classes of universal cotangent line bundles $\{ \psi_1, \ldots, \psi_n \}$ (known as $\psi$-classes) on $M_{\gamma,n}$. The generating function of the intersection numbers was conjectured and later proven to be the tau function of KdV hierarchy by Witten and Kontsevich respectively [39, 24].

In 2017, Kontsevich-Soibelman [25] introduced the notion of Airy structures which is given by a Lie algebra $\mathfrak{g}$ generated by a set of quadratic polynomials $\{ H_{1,\alpha} \}$ of a certain form on a symplectic vector space $W$ where the Lie bracket is naturally given by the Poisson bracket on $W$. They showed that any Airy structure corresponds to a recursion called abstract topological recursion. This reduces to the usual Eynard-Orantin topological recursion when considering an example of Airy structure $\{ H_{1,\alpha} \} := \{ (H_{\text{Airy}})_{k=1,2,3,\cdots} \}$ and $W := W_{\text{Airy}}$ arises from the so-called residue constraints. The zero generators of $\mathfrak{g}$ is a Lagrangian submanifold $L \subset W$ by the fact that $\mathfrak{g}$ is closed under the Lie bracket. We call $L$ a quadratic Lagrangian submanifold since it is defined by a set of quadratic polynomials. In particular, we let $L_{\text{Airy}} := \{ (H_{\text{Airy}})_{k=1,2,3,\cdots} = 0 \} \subset W_{\text{Airy}}$. 
Let us return to the discussion of the particular Airy structure \( \{ (H_{Airy})_{k=1,2,3,\ldots} \} \) corresponding to topological recursion. Let \( Discs^{Ram} \) be a space of \( \{ Ram \} \)-disjoint union of discs \( \mathbb{D}_\alpha, \alpha \in Ram \) embedded inside the foliated symplectic surface \( S \). Each \( \mathbb{D}_\alpha \) are deformed Airy curves which can be parameterized by

\[
z_\alpha \mapsto \left( x_\alpha = z_\alpha^2 + a_\alpha, y_\alpha = \sum_{k=1}^{\infty} b_{k\alpha} z_\alpha^k \right)
\]  

(1.3)
on the local coordinates chart, \( (U_\alpha, x_\alpha, y_\alpha) \) of \( S \) with the ramification point \( r_\alpha = (x_\alpha, y_\alpha) = (a, b_\alpha) \in U_\alpha \). Given an annulus on a disc \( \mathbb{D}_\alpha \) centered at \( r_\alpha \), the set of all Laurent series which converge on the annulus naturally has a structure of an infinite dimensional symplectic vector space. The infinite-dimensional symplectic vector space \( W^{Ram}_{Airy} \) is given by the direct sum these vector spaces over \( \alpha \in Ram \). The space \( Discs^{Ram} \) can be thought of as the local version of the moduli space of curves \( B \). Introduce a trivial vector bundle \( W^{Ram} \to Discs^{Ram} \) with fiber over any point given by \( W^{Ram}_{Airy} \) equipped with a certain connection \( \nabla \). Let us fix a reference point \( t_0 \in Discs^{Ram} \) and let \( Discs^{Ram}_{t_0} \supset t_0 \) be a certain subset of \( Discs^{Ram} \) analogous to \( B_{\Sigma_0} \). The important observation is that there exists a local section \( \theta \) of \( W^{Ram} \) on \( Discs^{Ram}_{t_0} \) such that the parallel transport of \( \theta_t \in W^{Ram}_{t_0} \) from any point \( t \in Discs^{Ram}_{t_0} \) to \( t_0 \) gives an embedding of \( Discs^{Ram}_{t_0} \) into the fiber \( W^{Ram}_{t_0} \) with the image contained in the quadratic Lagrangian submanifold \( L^{Ram}_{Airy} \). The section \( \theta \) can be thought of as that of a local version of \( dS \) or a Seiberg-Witten differential.

At first glance, this ongoing discussion seems to have little to do with the deformation of curves or Seiberg-Witten theory. But we note that an infinitesimal deformation of a smooth curve \( \Sigma \) will produce a global holomorphic section of the normal bundle on \( \Sigma \). If \( \Sigma \) is embedded inside a symplectic surface, then by applying the symplectic form to the global section of the normal bundle, we produce a global holomorphic form on \( \Sigma \) which naturally arises from the infinitesimal deformation of \( \Sigma \). In particular, let \( B \) be the moduli space of \( F \)-transversal genus \( g \) curves, then we have the map \( \phi_{\Sigma, t} : T_{[\Sigma]} B \to \Gamma(\Sigma, \Omega^1_{\Sigma}) \hookrightarrow \mathcal{H}_{\Sigma} \) for each \([\Sigma] \in B \). It is possible to check that \( d_{\mathcal{G}_{\Sigma}} \phi = 0 \) where \( d_{\mathcal{G}_{\Sigma}} \phi \) denotes the exterior covariant derivative using the Gauss-Manin connection. Let us fix a reference point \([\Sigma_0] \in B \). By the Pointcaré Lemma, there exists an open neighbourhood \( B_{\Sigma_0} \) of \([\Sigma_0] \) with a local section \( \theta \) of \( \mathcal{H} \) on \( B_{\Sigma_0} \) such that \( d_{\mathcal{G}_{\Sigma}} \theta = \phi \). Then the parallel transport of \( \theta_{\Sigma} \in \mathcal{H}_{\Sigma} \) from any point \([\Sigma] \in B_{\Sigma_0} \) to \([\Sigma_0] \) defines an embedding of \( B_{\Sigma_0} \) into \( \mathcal{H}_{\Sigma_0} \) as a Lagrangian submanifold \( L_{\Sigma_0} \). This is exactly the same embedding given in (1.2) with

\[
a^i := a^i(\Sigma) = \oint_{A_i} \theta_{\Sigma}, \quad b_i := b_i(\Sigma) = \oint_{B_i} \theta_{\Sigma} = \frac{\partial \mathcal{F}_{\Sigma_0}(\{ a^k \})}{\partial a^i}, \quad i = 1, \ldots, g,
\]

where the holomorphic function \( \mathcal{F}_{\Sigma_0} = \mathcal{F}_{\Sigma_0}(\{ a^k \}) \) defined on \( B_{\Sigma_0} \) is the generating function of \( L_{\Sigma_0} \) called the prepotential. For each \([\Sigma] \in B_{\Sigma_0} \), we may consider a lift of the cohomology class \( \theta_{\Sigma} \) to a differential form on \( \Sigma \). Such a lift is not unique since an addition by \( \theta \) which changes its cohomology class. However, the key idea of Kontsevich-Soibelman is there exists exactly one lift \( \theta^{\Sigma} \) of \( \theta_{\Sigma} \) such that the direct sum of Laurent series expansions of \( \theta^{\Sigma} \) at each ramification point coincides with \( \theta_t \in W^{Ram}_{t_0} \). Here, \( t \in Discs^{Ram}_{t_0} \) is given in term of \([\Sigma] \in B_{\Sigma_0} \) by the disjoint union of some open neighbourhood \( \mathbb{D}_\alpha(\Sigma) \subset \Sigma \subset S \) which we shall denote by \( t = \gamma(\Sigma) \). The image of \( \theta_t \) under the parallel transport from \( t \) to \( t_0 \) is contained inside \( L^{Ram}_{t_0} \subset W_{t_0}^{Ram} \).

In the end, we get a family of differential forms \( \theta^{\Sigma} \) which relates the Lagrangian submanifold \( L_{\Sigma_0} \subset \mathcal{H}_{\Sigma_0} \) with the quadratic deformation of the symplectic manifold \( L_{Airy}^{Ram} \subset W_{t_0}^{Ram} \) and each \( \theta^{\Sigma} \) can be thought of as a generalized Seiberg-Witten differential \( dS \) satisfying \([1,1] \). We can understand the relationship between \( L_{\Sigma_0} \) and \( L_{Airy}^{Ram} \) more geometrically. The map \( [\Sigma] \mapsto \gamma(\Sigma) \) embeds \( B_{\Sigma_0} \) as a subset of \( Discs^{Ram}_{t_0} \) and \( L_{\Sigma_0} \) is a cohomological image in \( \mathcal{H}_{\Sigma_0} \) of the cross-section of \( L_{Airy}^{Ram} \subset W_{t_0}^{Ram} \) over \( B_{\Sigma_0} \subset Discs^{Ram}_{t_0} \). The quadratic Lagrangian submanifold \( L_{Airy}^{Ram} \) can be regarded as universal in the following sense. Any two Langrangian submanifolds \( L_{\Sigma_0}, L_{\Sigma}' \) arise from two different moduli spaces \( B, B' \) of \( F \)-transversal curves with the same number of genus and ramification points will correspond to two different cross-sections of \( L_{Airy}^{Ram} \).

**Theorem 2.77.3** Let \( B \) be the moduli space of \( F \)-transversal genus \( g \) curves in a foliated symplectic surface \( S \). Then for some small open neighbourhood \( B_{\Sigma_0} \subset B \) of the reference point \([\Sigma_0] \in B \), the prepotential \( \mathcal{F}_{\Sigma_0} = \mathcal{F}_{\Sigma_0}(a^1, \ldots, a^g) \) can be expressed as

\[
\mathcal{F}_{\Sigma_0}(a^1, \ldots, a^g) = \mathcal{F}_{\Sigma_0}(a^1_0, \ldots, a^g_0) + \sum_{i=1}^{g} (a^i - a^i_0) \frac{\partial \mathcal{F}_{\Sigma_0}}{\partial a^i}(a^1_0, \ldots, a^g_0) + \frac{1}{2} \sum_{i,j=1}^{g} (a^i - a^i_0)(a^j - a^j_0) \frac{\partial^2 \mathcal{F}_{\Sigma_0}}{\partial a^i \partial a^j}(a^1_0, \ldots, a^g_0) + \sum_{n=3}^{\infty} \frac{1}{n!} \left( \frac{1}{2\pi i} \right)^{n-1} \sum_{t_1, \ldots, t_n=1}^{g} \left( \oint_{p_{1} \in B_{t_1}} \cdots \oint_{p_{n} \in B_{t_n}} \omega_{0,n}(p_1, \ldots, p_n) \right) (a^{i_1} - a^{i_1}_0) \cdots (a^{i_n} - a^{i_n}_0)
\]

(1.4)
for all \( \{a^1, \ldots, a^g\} = [\Sigma] \in \mathcal{B}_{\Sigma_0} \). Where \( a^k \) := \( a^k(\Sigma_0) \) and the multi-differentials \( \{\omega_{g,n} \in \Gamma((\Sigma_0 \setminus \cup_{a \in \text{Ram} \tau_n})^n, (\Omega_{\Sigma_0}^{2g,n})) \} \) are produced from topological recursion on \( \Sigma_0 \).

The interesting point about Theorem 2.7.3 is that the prepotential \( \mathfrak{F}_{\Sigma_0} \) contains information about the deformation of curves \( \Sigma \) within the moduli space \( \mathcal{B} \) whereas \( \omega_{0,n} \) is produced from topological recursion, which is done on a single curve \( \Sigma_0 \) without any knowledge on the moduli space it belongs to.

We are going to revisit in detail all the discussions about Airy structures, deformations of curves, and topological recursion later in Chapter 2 along with the proof of Theorem 2.7.3. To apply this result to the Seiberg-Witten family of curves we need to find a foliated symplectic surface \( S \) such that each Seiberg-Witten curve can be embedded as a \( J \)-transversal curve. It turns out that such a foliated symplectic surface exists as we are going to show in Chapter 3, hence there is a nice relationship between the Seiberg-Witten prepotential \( \mathfrak{F}_{\Sigma_0} \) and the genus zero part of topological recursion on Seiberg-Witten curve with \( \omega_{0,1} = dS_{SW} \).

The formula (1.4) can also be obtained via the Rauch variational formula [16] [14] [3]. For example, Bagaria-Huang [3] studied the moduli space \( B \) of curves \( \Sigma \) arising from the Hitchin systems, where each \( \Sigma \) is embedded inside the total space of the cotangent bundle \( T^*C \) of some compact Riemann surface \( C \). They showed that the Rauch variational formula holds in this case and that the formula (1.4) follows. Theorem 2.7.3 generalizes the result by Bagaria-Huang to the case where \( S \) is an arbitrary foliated symplectic surface instead of \( T^*C \). Moreover, even in the \( S = T^*C \) case, our approach of proving the formula via the idea of Kontsevich-Soibelman should shed light on some interesting underlying geometries between the Lagrangian submanifold in \( \mathcal{H}_{\Sigma_0} = H^1(\Sigma_0, \mathbb{C}) \) given by the cohomology of the tautological 1-form and the quadratic Lagrangian submanifolds with \( \omega_{0,n} \) as the generating function.

Closely related to topological recursion and many other branches of mathematics is the notion of a Frobenius manifold which was introduced by Dubrovin in the 1990’s [11] [9]. A smooth manifold is a Frobenius manifold if the tangent space at each point carries a structure of an unital commutative associative algebra known as Frobenius algebra with some other additional data. Any Frobenius manifold is locally described by a holomorphic function called Frobenius potential satisfying the Witten-Dijkgraaf-Verlinde-Verlinde (WDVV) equations due to the associativity of the Frobenius algebra. Conversely, any holomorphic function satisfying the WDVV equation also defines a structure of a Frobenius manifold. Remarkably there exists an equivalence between Frobenius manifolds and genus zero Cohomological Field Theory (CohFT) [28], therefore, despite its simplicity, Frobenius structures contain a lot of interesting information. Let us consider a CohFT \( \{\Omega_{g,n} : V^* \rightarrow H^*(\mathcal{M}_{g,n}, \mathbb{C})\} \) for some \( \mathbb{C} \)-vector space \( V \) with a basis \( \{e_1, \ldots, e_{\dim V}\} \). The descendant CohFT potential is given by

\[
F(\{t^{d,k}\}) := \sum_{g \geq 0} h^{g-1} \sum_{n \geq 1} \sum_{I_1, \ldots, I_n, d_1, \ldots, d_n \in \mathbb{Z}_{\geq 0}} \frac{t^{d_1, I_1} \cdots t^{d_n, I_n}}{n!} \int_{\mathcal{M}_{g,n}} \Omega_{g,n}(e_{i_1} \otimes \cdots \otimes e_{i_n}) \psi_{d_1} \cdots \psi_{d_n}
\]

where \( \psi_i \) are \( \psi \)-classes on \( \mathcal{M}_{g,n} \). The correlators are given by the derivatives of \( F(\{t^{d,k}\}) \) evaluated at \( \{t^{d,k} = 0\} \). By the properties of CohFTs, under a pull-back to a boundary divisor, it follows that the genus zero descendant-free part \( (g = 0, t^{d>0,k} = 0) \) of \( F(\{t^{d,k}\}) \) satisfies the WDVV equations and therefore defines a Frobenius potential. Conversely, it can be shown that given a Frobenius manifold, its Frobenius potential is the generating function of a genus zero CohFT \( \{\Omega_{0,n} : V^* \rightarrow H^*(\mathcal{M}_{g,n}, \mathbb{C})\} \). Moreover, if a Frobenius manifold happens to be semisimple then the all-genus CohFT \( \{\Omega_{g,n} : V^* \rightarrow H^*(\mathcal{M}_{g,n}, \mathbb{C})\} \) can be reconstructed from the genus zero data [35]. Finally, there is a known correspondence between the genus zero data of a CohFT and topological recursion. A spectral curve can be chosen such that \( \omega_{g,n} \) produced from topological recursion can be expanded as a polynomial in some auxiliary differentials where coefficients are given by the correlators of the CohFT reconstructed [12] [13].

Dubrovin proposed in 2004 [10] that the Seiberg-Witten family of curves can be studied in terms of 2g-dimensional tensor products of Frobenius manifolds \( M_{A_g} \otimes QH^*(\mathbb{P}^1) \), where \( M_{A_g} \) is the \( A_g \)-Coxeter Frobenius manifold and \( QH^*(\mathbb{P}^1) \) is the quantum cohomology of \( \mathbb{P}^1 \). In general, the definition of the tensor product of Frobenius manifolds \( M = M' \otimes M'' \) is given by the cup product of the corresponding CohFTs [22]. First, let us recall from [10] the notion of dual (almost) Frobenius manifold \( M \), which can be obtained on the given Frobenius manifold \( M \) in a certain way as a new structure satisfying all the axioms of Frobenius manifolds except the covariance constancy of the unit vector field. As usual, given the Levi-Civita connection \( \nabla \) on \( M \), we may consider the deformed flat connection \( \tilde{\nabla} \) on \( M \) with deformation parameter \( \nu \). We call any function \( f = f(t; \nu) \) on \( M \) such that \( \tilde{\nabla} \text{df} = 0 \) a \( \nu \)-period and an odd period if \( \nu = \frac{1}{2} \). There exists a symplectic structure

\footnote{More precisely we should say Formal Frobenius manifolds [28], Definition 1.1.1, Chapter III, which is slightly different from the Frobenius manifolds we will introduce and work with in Chapter 4. All Frobenius manifolds are locally formal but not the other way around. A Formal Frobenius manifold consists of a \( C \)-vector space \( V \), a non-degenerate symmetric pairing \( (., .) : V \times V \rightarrow C \) and a formal series (Frobenius potential) \( F \in \mathbb{C}[[V]] \) satisfying the WDVV equation. No additional structure such as a flat unity vector field or an Euler vector field (see A3, Definition 1.1.2) are required.}
on $M_{A_0} \otimes QH^*(\mathbb{P}^1)$ and a natural family of Lagrangian submanifolds $L_\Lambda$ parameterized by the energy scale $\Lambda$ called the \textit{coordinates cross}. The system of $2g$-linearly independent odd periods of $M_{A_0} \otimes QH^*(\mathbb{P}^1)$ restricted to each $L_\Lambda$ is given by $A$ and $B$-periods of the Seiberg-Witten differential $dS_{SW}$ on the Seiberg-Witten family of curves parameterized by $L_\Lambda$. It follows that the generating function of $L_\Lambda$ is given by the Seiberg-Witten prepotential $H_{SW}^\Lambda (t^\prime', \Lambda)$. In other words, by assigning the structure of Frobenius manifold $M_{A_0} \otimes QH^*(\mathbb{P}^1)$ to $H_{SW} = H^1(\Sigma, \mathbb{C})$ with canonical coordinates given by odd periods, we find that the image of $B_{\Sigma_0}$ embedded inside $H_{SW}$ is given by $L_\Lambda$.

It is unclear at this point why the Seiberg-Witten family of curves arises from the tensor product of Frobenius manifold $M_{A_0} \otimes QH^*(\mathbb{P}^1)$. However, we will show that it is natural for $\nu$-periods of any general tensor product Frobenius manifold $M = M' \otimes M''$ to be written as a period integral on some family of Riemann surfaces. In particular, we have the following:

**Theorem 4.5.1** Let $M'$ and $M'$ be $u'$ and $u''$-dimensional Frobenius manifolds respectively. Suppose that $\xi' = \xi'(t'; \nu'; \lambda) := dx'(t'; \nu'; \lambda)$ is a gradient of a $(\nu', \lambda)$-period $x'(t'; \nu'; \lambda)$ of $M'$ and $\xi'' = \xi''(t''; \nu''; \lambda) := dx''(t''; \nu''; \lambda)$ is a gradient of $(\nu'', \lambda)$-period $x''(t''; \nu''; \lambda)$ of $M''$ then

$$
\psi(t', t''; \nu) = \int_C \xi'(t'; \nu'; -\lambda) \otimes \xi''(t''; \nu''; +\lambda) d\lambda
$$

(1.5)

is a gradient of $\nu$-period on coordinates cross of $M = M' \otimes M''$ where $\nu = \nu' + \nu'' + 1/2$ and $C$ is an arbitrary closed contour on a Riemann surface where the integrand is well-defined.

This result allows us to start from the Seiberg-Witten theory and deduce that the $A$ and $B$-periods of $dS_{SW}$ are odd periods on $M = M_{A_0} \otimes QH^*(\mathbb{P}^1)$. This is done by observing that $dS_{SW}$ can be written as a product of $(\nu = 0)$-periods of two other known Frobenius manifolds $M' = M_{A_0}$ and $M'' = QH^*(\mathbb{P}^1)$ and invoke Theorem 4.5.1.

It remains an open question at this stage whether other families $B$ of curves can be embedded as a Lagrangian submanifold inside some tensor product Frobenius manifold. It is also interesting to note that not recasting Seiberg-Witten theory in terms of a Frobenius manifold will enable us to use some reconstruction techniques to extend Theorems 2.7.3 to some higher genera statements involving $\omega_{g,n}$, $g \geq 1$. We will leave these topics to be discussed in future works.

Let us summarize the structure of this thesis as follows:

**Chapter 1** General introduction and review of the Seiberg-Witten theory.

**Chapter 2** A joint work with Paul Norbury, Michael Swaddle, and Mehdi Tavakol, expanding upon the work by Kontsevich-Soibelman [25] on the relationship between Airy structures, deformation of curves and topological recursion. We will show how the relationship between the prepotential of the moduli space of curves in a foliated symplectic surface and the genus zero part of topological recursion follows from the idea of Kontsevich-Soibelman.

**Chapter 3** A joint work with Paul Norbury examining the Seiberg-Witten family of curves using the framework of Kontsevich-Soibelman [25]. The Seiberg-Witten family of curves will be used as an explicit example to illustrate some computations involved in Chapter 2 leading to the relationship between Seiberg-Witten prepotential and the genus zero part of topological recursion on the Seiberg-Witten curves.

**Chapter 4** An original work based on the work by Dubrovin [10] concerning the relationship between Seiberg-Witten curves and Frobenius manifold. We present a general formula for odd periods on the coordinates-cross of tensor product Frobenius manifold which would reduce to the version considered by Dubrovin that leads to Seiberg-Witten curves.

### 1.1 Seiberg-Witten Family of Curves

In this section, we give a quick summary of the needed mathematical details of the Seiberg-Witten family of curves. More comprehensive reviews of this material can be found abundantly in the literature such as [21, 29, 31]. The information of $SU(N)$ Seiberg-Witten theory can be encoded into a genus $g = N$ family $\mathcal{B}$ of \textit{Seiberg-Witten curves} $\Sigma$ given by

$$
\Lambda^{g+1} \left( w + \frac{1}{w} \right) = z^{g+1} + u^2 z^{g-1} + \ldots + u^1 =: P(z; u)
$$

(1.6)
where \( \{ u^i, \ldots, u^g \} \) are the coordinates of \( B \). Occasionally, we will write the curve \( \Sigma \) as \( \Sigma(u) \) to emphasize its dependence on \( u = (u^1, \ldots, u^g) \). We may regard \( dS \) as a plane curve equation, in that case, we have \( w, z \in \mathbb{C} \) and \( \Sigma(u) \subset \mathbb{C}^2 \) as a non-compact curve. The compactification of \( \Sigma(u) \) is obtained by adding two points \( \infty_+ = (w, z) = (\infty, \infty) \) and \( \infty_- = (w, z) = (0, 0) \). In this way, we regard \( \Sigma(u) \) defined in \( (1.6) \) as a compact smooth curve. The map \( \pi : \Sigma(u) \to \mathbb{P}^1(w, z) \mapsto z \) is a double cover that shows that \( \Sigma(u) \) is a hyperelliptic curve with the hyperelliptic involution given by \( (w, z) \leftrightarrow (1/w, z) \). An alternative way to express \( (1.6) \) is

\[
y^2 = P^2(z; u) - 4A^{2g+2}
\]

which makes it even more obvious that \( \Sigma(u) \) is a hyperelliptic curve with the hyperelliptic involution \( (y, z) \leftrightarrow (-y, z) \). The \( 2g + 2 \) ramification points of \( \pi \) are given by \( (y, z) = (0, z^{\pm}) \) where \( z^{\pm}, i = 1, \ldots, g + 1 \) are the roots of the polynomial \( P(z; u) \pm 2A^{g+1} = 0 \). We can check that the curve \( \Sigma(u) \) is smooth unless \( P'(z^{\pm}; u) = 0 \) or \( P'(z^{-}; u) = 0 \). In other words, we may define the family of smooth Seiberg-Witten curves to be

\[
B^{reg} := \{ u = (u^1, \ldots, u^g) \in B \mid P^2(z; u) - 4A^{2g+2} = 0 \text{ has } 2g + 2 \text{ distinct roots} \} \subset B.
\]

We note that \( B^{reg} \) is dense inside \( B \) and since we will mainly be interested in smooth Seiberg-Witten curves in our works, we will relabel \( B^{reg} \) as \( B \) for simplicity.

We define the Seiberg-Witten differential to be the meromorphic differential form

\[
dS_{SW} := z \frac{dw}{w} = \frac{zP'(z; u) dz}{y}
\]

defined on each Seiberg-Witten curve \( \Sigma(u) \) with residueless poles of order 2 at \( \infty_+ \in \Sigma(u) \). Occasionally we will write \( dS_{SW}(\Sigma(u)) \) if we want to emphasize the specific \( dS_{SW} \) defined on \( \Sigma(u) \). Let us check that the variations of \( dS_{SW}(\Sigma(u)) \) within the family \( B \) produce global holomorphic forms on \( \Sigma(u) \), hence \( dS_{SW} \) satisfies \( (1.1) \). As we have mentioned, a choice of connection must be specified in order for the derivatives \( \frac{\partial}{\partial u^j} \) to makes sense, in this case let us keep \( w = \text{const} \), we have

\[
\left. \frac{\partial dS}{\partial u^i} \right|_{w=\text{const}} = \left. \frac{\partial z}{\partial u^i} \right|_{w=\text{const}} \frac{dw}{w} = -z^{i-1} \frac{dw}{P'(z; u) w} = \frac{z^{i-1} dz}{y}, \quad i = 1, \ldots, g.
\]

which are holomorphic on \( \Sigma(u) \). We define

\[
a^i := \oint_{A_i} dS_{SW}, \quad b_i := \oint_{B_i} dS_{SW}, \quad i = 1, \ldots, g.
\]

We note that \( \{ a^1, \ldots, a^g \} \) gives another set of holomorphic coordinates for \( B \). We can see this by noting that \( \frac{\partial a^i}{\partial u^j} \) is invertible because if \( \sum_{i=1}^g c_i \frac{\partial a^i}{\partial u^j} = \oint_{A_i} \sum_{i=1}^g c_i z^{i-1} dz = 0 \) for all \( j, k = 1, \ldots, g \) and for some constants \( c_i \in \mathbb{C} \) then \( \sum_{i=1}^g c_i z^{i-1} dz = 0 \) because it is a holomorphic form with zero \( A \)-periods. It follows that \( \frac{\partial dS_{SW}}{\partial u^i} = a_i \) are normalized holomorphic differentials:

\[
\oint_{A_j} \omega_i = \delta^i_j, \quad \oint_{B_j} \omega_i = \frac{\partial b_i}{\partial u^j} =: \tau_{ij},
\]

where \( b_i = b_i(a^1, \ldots, a^g) \) is treated as a holomorphic function of \( \{ a^{i=1, \ldots, g} \} \). The standard argument involving Riemann bilinear identity shows that \( \tau_{ij} = \tau_{ji} \):

\[
0 = \frac{1}{2\pi i} \sum_{k=1}^g \left( \oint_{A_k} \omega_i \oint_{B_k} \omega_j - \oint_{A_k} \omega_i \oint_{A_k} \omega_j \right) = \frac{1}{2\pi i} (\tau_{ij} - \tau_{ji}).
\]

In other words, \( \frac{\partial}{\partial a^i} = \frac{\partial b_i}{\partial u^j} \) therefore, by Poincaré lemma given any \( \Sigma_0 \in B \) there exists an open neighbourhood \( \mathcal{B}_{\Sigma_0} \ni [\Sigma_0] \) with a holomorphic function \( \mathfrak{F}_{\Sigma_0}^{SW} = \mathfrak{F}_{\Sigma_0}^{SW}([a^k], \Lambda) \) such that

\[
b_i = \frac{\partial \mathfrak{F}_{\Sigma_0}^{SW}([a^k], \Lambda)}{\partial u^i}.
\]

We call \( \mathfrak{F}_{\Sigma_0}^{SW} = \mathfrak{F}_{\Sigma_0}^{SW}([a^k], \Lambda) \) the Seiberg-Witten prepotential. The expansion of \( \mathfrak{F}_{\Sigma_0}^{SW} \) can be computed via Nekrasov’s partition function \cite{33,34} or Nakajima’s blow-up formula \cite{31,30} or by computing the odd periods of \( M_{A_y} \otimes QH^*(\mathbb{P}^1) \) Frobenius manifold \cite{10}. 

10
Chapter 2

Airy Structures and Deformation of Curves

In this chapter, we summarize the work of Kontsevich-Soibelman \[25\] on Airy structures, topological recursion, and the moduli space of curves in a foliated symplectic surface. In particular, there are 3 important ideas from \[25\] which we are going to explore:

1. The quantization of Airy structures leads to a generalized version of topological recursion. The usual Eynard-Orantin topological recursion corresponds to an example of Airy structure given by the so-called residue constraints.

2. A deformation of an Airy curve \( y^2 = x \), i.e. a disc, inside a foliated symplectic surface produces a differential form satisfying the residue constraints.

3. The cohomology class, arising from the deformation of a curve in a foliated symplectic surface, can be lifted to the differential form on the curve, which locally agrees near each ramification point with the differential form produced from the deformation of a disc.

Connecting these ideas leads to a nice relationship between the prepotential and the genus zero part of topological recursion which is the content of Theorem 2.7.3, the main result of this chapter. We are going to start in Section 2.1 by reviewing some basic deformation theory of curves \( \Sigma \) in a foliated symplectic surface \((S, \Omega_S, F)\), following \[25\], Section 4. This eventually leads to an embedding of a Lagrangian submanifold in \( H^1(\Sigma, \mathbb{C}) \) and establishes the notion of prepotential in this general context. Section 2.2 reviews definitions and basic results concerning Airy structures, including the corresponding quadratic Lagrangian submanifold, quantization of Airy structures, and abstract topological recursion, all of which can be found in Section 1-3 of \[25\]. An important example of an Airy structure arises from residue constraints as introduced in \[25\], Section 3.3 will be discussed in Section 2.3.

We have been following the material in \[25\] closely so far, and we will be for the rest of this chapter. However, for the remaining sections, with an exception of Section 2.6, we are going to approach the subject from an analytical perspective rather than a more algebraic treatment of \[25\]. In particular, we will replace all formal power series with power series converges on some annulus. We believe that this should be a more natural way to arrive at our main result involving the prepotential which is a holomorphic function.

We study the analytic version of residue constraints Airy structure in Section 2.4. In particular, we look at the deformation of analytic discs and show that an embedding of a neighbourhood in the space of all discs gives an analytic solution to the residue constraints, as explained in \[25\], Section 6. The connection between the ‘global’ deformations, as studied in Section 2.1 with the ‘local’ deformations, studied in terms of discs in Section 2.4 will be discussed in Section 2.5 analytically, with a summary given by Proposition 2.5.38 \[25\], Proposition 7.1.2. In Section 2.6 we review the well-known result from \[25\], Section 3 how Eynard-Orantin topological recursion arises from the residue constraints Airy structure. At last, we prove our main result, Theorem 2.7.3 in Section 2.7. We argue that when specializing to an example of a family of curves arises from the Hitchin systems \[20\], \[3\], our result agrees with the result previously obtained by Baraglia-Huang \[3\], Theorem 7.4 using a different technique. An application of Theorem 2.7.3 to the Seiberg-Witten family of curves will also be briefly mentioned before a more extensive discussion in Chapter 3.
2.1 Deformation of Curves in Foliated Symplectic Surfaces

2.1.1 Foliated symplectic surfaces

Let us start by fixing some frequently used definitions which should be standard in complex geometry:

**Definition 2.1.1** A 2n-dimensional holomorphic symplectic manifold \((X, \Omega_X)\) is a 2n-dimensional complex manifold \(X\) equipped with a holomorphic closed non-degenerates 2-form \(\Omega_X\), i.e. at any point \(x \in X\), \(\Omega_{X,x} : T_xX \times T_xX \to \mathbb{C}\) is a non-degenerate anti-symmetric bilinear form on the holomorphic tangent space \(T_xX\).

**Definition 2.1.2** Let \((X, \Omega_X)\) be a holomorphic symplectic manifold. A complex submanifold \(L \subset X\) is a holomorphic Lagrangian submanifold if for every \(x \in L\), \(T_xL \subset T_xX\) is a maximal isotropic subspace, i.e. \(T_xL\) is a maximal subspace of \(T_xX\) such that \(\Omega_{X,x} | T_xL = 0\).

Since no other types of symplectic manifolds or Lagrangian submanifolds will be considered in this work, we are going to refer to \((X, \Omega)\) and \(L \subset X\) in the above definitions simply as **symplectic manifold** and **Lagrangian submanifold** respectively, omitting the term ‘holomorphic’. Definition 2.1.1 and Definition 2.1.2 also make sense when \(X\) is infinite-dimensional, in that case any Lagrangian submanifold \(L \subset X\) will also be infinite-dimensional. On the other hand, when \(X\) is finite-dimensional, it is common to replace the maximal isotropic subspace condition in Definition 2.1.2 with \(\dim L = \frac{1}{2} \dim X\). If \((X, \Omega_X)\) and \(L \subset X\) are complex vector spaces, then we also call them a symplectic vector space and a Lagrangian subspace respectively.

**Definition 2.1.3** An \(m\)-dimensional holomorphic foliation \(\mathcal{F}\) on an \(n\)-dimensional complex manifold \(X\) is a decomposition of \(X\) into a disjoint union of connected \((n-m)\)-dimensional complex submanifolds \(\{L_\alpha\}\) called the leaves of the foliation satisfying the following property: At every point, \(x \in X\) there exists an open neighbourhood \(U \ni x\) and a system of local holomorphic coordinates \((x^1, \ldots, x^n)\) such that for each leaf \(L_\alpha\), each component of \(L_\alpha \cap U\) is given by \(\{x^{m+1} = \text{const}, \ldots, x^n = \text{const}\}\).

In the case where \(X\) is a surface, \(n = 2\) we choose \(m = 1\) and we will refer to a 1-dimensional foliation \(\mathcal{F}\) of \(X\) simply as a foliation \(\mathcal{F}\) of \(X\). The leaves of a 1-dimensional foliation \(\mathcal{F}\) of \(X\) are Lagrangian for dimensional reasons.

**Definition 2.1.4** Let \((S, \Omega_S, \mathcal{F})\) be a foliated symplectic surface \(S\) with a symplectic form \(\Omega_S\) and a foliation \(\mathcal{F}\). Let \(U \subseteq S\) be an open subset with a coordinates system \((x, y)\) such that \(\Omega_S|U = dx \wedge dy\) and the foliation \(\mathcal{F}\) is given locally on \(U\) by the equations \(x = \text{const}\). We call \((x, y)\) a \((\mathcal{F}, \Omega_S)\)-local coordinate system and call \((U, x, y)\) a \((\mathcal{F}, \Omega_S)\)-chart.

**Lemma 2.1.5** ([25 Section 4.1]) Given any point \(p \in S\) there exists a \((\mathcal{F}, \Omega_S)\)-chart \((U_p, x_p, y_p), U_p \subseteq S\) containing \(p\).

**Proof:** By Definition 2.1.3 we choose a local coordinate system, \((\bar{x}_p, \bar{y}_p)\) on some open set \(\bar{U}_p \ni p\) such that leaves of the foliation \(\mathcal{F}\) are given by \(\bar{x}_p = \text{const}\). Using this coordinate system, the symplectic form can be written as \(\Omega_S = \Omega_S(\bar{x}_p, \bar{y}_p) \, d\bar{x}_p \wedge d\bar{y}_p\). Consider a coordinates transformation of the form

\[
\bar{x}_p = x_p, \quad \bar{y}_p = G(x_p, y_p),
\]

so that the leaves of foliation are still given by \(x_p = \text{const}\). Without loss of generality, let us suppose that \((x_p, y_p) = (0, 0)\) is the point \(p \in S\). The symplectic form becomes

\[
\Omega_S = \Omega_S(x_p, G(x_p, y_p)) \, dx_p \wedge \left( \frac{\partial G}{\partial x_p}dx_p + \frac{\partial G}{\partial y_p}dy_p \right) = \Omega_S(x_p, G(x_p, y_p)) \frac{\partial G}{\partial y_p} \, dx_p \wedge dy_p.
\]

Therefore, we need to find \(G = G(x_p, y_p)\) such that \(\Omega_S(x_p, G(x_p, y_p)) \frac{\partial G}{\partial y_p} = 1\). Integrating this equation, we get that \(G\) is implicitly defined by \(\Omega_S(x_p, y_p, G) = \int_0^y \Omega_S(x_p, \tau) \, d\tau - y_p + C = 0\) for some constant \(C\). Let us pick \(C = 0\), although this choice is arbitrary. We have \(\Omega_S(0, 0, 0) = 0\) and \(\frac{\partial G}{\partial y_p}(0, 0, 0) = \Omega_S(0, 0) \neq 0\) because the symplectic form is non-degenerates by definition. Therefore, we can apply the complex implicit function theorem to conclude that there exists \(G = G(x_p, y_p)\) holomorphic on some open neighbourhood \(U\) of \(p = (x_p = 0, y_p = 0)\). \(\square\)
We note that the \((F, \Omega_S)\)-local coordinates in the neighbourhood of a point \(p \in S\) is not unique. In fact, given a \((F, \Omega_S)\)-local coordinates \((x, y)\), any new coordinates \((\tilde{x}, \tilde{y})\) under the transformation of type

\[
\tilde{x} = F(x), \quad \tilde{y} = \frac{y}{F'(x)} + G'(x)
\]  

(2.1)

will also be \((F, \Omega_S)\)-local coordinates where \(F\) and \(G\) are locally defined holomorphic functions and \(F'(x(p)) \neq 0\). In particular, \(F\) is any function locally bi-holomorphic in a neighbourhood of \(p\).

### 2.1.2 Deformation of \(F\)-transversal curves

**Definition 2.1.6** ([25], Definition 4.1.2]) A smooth compact complex curve \(\Sigma\) embedded inside a foliated symplectic surface \((S, \Omega_S, F)\) is called \(F\)-transversal if \(\Sigma\) is tangent to the leaves of \(F\) at only finitely many points, with tangency order 1. We call points on a \(F\)-transversal curve \(\Sigma\) where \(\Sigma\) is tangent to a leaf of foliation the ramification points \(\{r_{\alpha \in Ram(\Sigma)}\}\) where \(Ram(\Sigma)\) is an index set.

**Remark 2.1.7** Given a Riemann surface \(\Sigma\) and a holomorphic map \(f: \Sigma \to \mathbb{P}^1\), the term ‘ramification point’ traditionally refers to a point \(r \in \Sigma\) such that \(f\) can be locally written as \(f(z) = z^n\), for some \(n \in \mathbb{Z}_{\geq 2}\), using some holomorphic coordinates charts \((U, z)\) and \((V, w)\) around \(r\) and \(f(r)\) respectively. For us, instead of a map \(f: \Sigma \to \mathbb{P}^1\), we have the foliation \(F\). By Lemma 2.1.5, a \((F, \Omega_S)\)-(chart \((U_p, x_p, y_p)\) can be chosen around any point \(p \in \Sigma\), hence the foliation locally induces a map \(q \in \Sigma \cap U_p \mapsto x_p(q) \in \mathbb{C}\). Our usage of the term ‘ramification point’ follows from the fact that each \(r_{\alpha \in Ram(\Sigma)}\) are ramification points of these locally foliation induced maps. Additionally, the ‘tangency order 1’ condition means the ramification index of each ramification point is 2. Note that a different choice of \((F, \Omega_S)\)-chart \((U_p, x_p, y_p)\) will give a different local map \(q \mapsto x_p(q)\) but ramification points will be the same. This is because \(x_p = F_p(x_p)\) for some function \(F_p\) such that \(F'_p(x_p(q)) \neq 0\), \(q \in U_p\) by (2.1), hence \(dx_p|_{\Sigma} = F'_p(x_p)dx_p|_{\Sigma}\) means \(dx_p|_{\Sigma} = 0\) exactly when \(dx_p|_{\Sigma} = 0\).

Let \(\mathcal{B}\) be the complex analytic moduli space of \(F\)-transversal genus curves in \((S, \Omega_S, F)\). We are going to show later that the dimension of \(\mathcal{B}\) is \(g\). We write \([\Sigma] \in \mathcal{B}\) for the point in \(\mathcal{B}\) corresponding to a \(F\)-transversal curve \(\Sigma\). Since the number of ramification points is constant for every \([\Sigma] \in \mathcal{B}\), we will simply write the index set as \(Ram = Ram(\Sigma)\). For any \(p \in \Sigma \subset S\) we find a \((F, \Omega_S)\)-(chart \((U_p, x_p, y_p)\) containing \(p\) according to Lemma 2.1.5. Let us think of \(x_p, y_p\) as functions \(\Sigma \cap U_p \to \mathbb{C}\), the ramification points \(\{r_{\alpha \in Ram(\Sigma)}\}\) are exactly where \(dx_p|_{\Sigma}\) vanishes and \(\Sigma\) has order 1. Consequently, if \(r_{\alpha} \notin \Sigma \cap U_p\), for all \(\alpha \in Ram\) then \(dx_p|_{\Sigma} \neq 0\) on \(\Sigma \cap U_p\) and we may assume that \(U_p\) is chosen small enough such that \(x_p\) is a local coordinate on \(\Sigma \cap U_p\) according to the inverse function theorem. On the other hand, if \(p = r_{\alpha} \in \Sigma, \alpha \in Ram\), we denote by \((U_{\alpha x}, x_{\alpha}, y_{\alpha})\) a \((F, \Omega_S)\)-chart such that \(\Sigma \cap U_{\alpha}\) is bi-holomorphic to a simply-connected open subset of \(\mathbb{C}\) with a local coordinate \(z_{\alpha} := \sqrt{x_{\alpha} - x_{\alpha}(r_{\alpha})}\).

**Definition 2.1.8** Given a \((F, \Omega_S)\)-(chart \((U_{\alpha x}, x_{\alpha}, y_{\alpha})\), we call the local coordinate \(z_{\alpha} := \sqrt{x_{\alpha} - x_{\alpha}(r_{\alpha})}\) on an open neighbourhood \(\Sigma \cap U_{\alpha}\) of the ramification point \(r_{\alpha}\) a **standard local coordinate**.

The parameterization of \(\Sigma \cap U_{\alpha}\) using the standard local coordinate takes the form

\[
(x_{\alpha} = a_{\alpha}(\Sigma) + z_{\alpha}^2, y_{\alpha} = b_{\alpha}(\Sigma) + b_{1\alpha}(\Sigma)z_{\alpha} + b_{2\alpha}(\Sigma)z_{\alpha}^2 + ...), \quad \alpha \in \Sigma, b_{\alpha}(\Sigma) \in \mathbb{C},
\]  

(2.2)

where \(b_{1\alpha}(\Sigma) \neq 0\) by the tangency order 1 condition. Therefore, we have \(dy_{\alpha}|_{\Sigma}(r_{\alpha}) \neq 0\) and \(y_{\alpha}\) is a local coordinate on some neighbourhoods of \(r_{\alpha}\). In particular, since \(S\) is compact, we can always cover \(S\) with a finite collection of \((F, \Omega_S)\)-charts \(\mathcal{U} = \{\{U_{\alpha x} \subset S, x_{\alpha} \in \mathbb{C}\}\}, \alpha \in \mathcal{S}\) is a finite index set, such that either \(x_{\alpha}\) or \(y_{\alpha}\) is a local coordinate on each \(\Sigma \cap U_{\alpha}\).

The following fact will be useful to us later:

**Lemma 2.1.9** ([25], Section 4.1 and 4.2]) Given \([\Sigma] \in \mathcal{B}\), there exists a \((F, \Omega_S)\)-(chart \((U_{\alpha x}, x_{\alpha}, y_{\alpha})\) containing the ramification point \(r_{\alpha} \in Ram(\Sigma)\) such that the parameterization of \(\Sigma \cap U_{\alpha}\) using the standard local coordinate \(z_{\alpha}\) takes the form \((x_{\alpha} = z_{\alpha}^2, y_{\alpha} = z_{\alpha})\). The \((F, \Omega_S)\)-(chart \((U_{\alpha x}, x_{\alpha}, y_{\alpha})\) is unique up to the \(\mathbb{Z}_3\) automorphism action \(x \mapsto \xi x, y \mapsto \xi y\), where \(\xi\) is a third-root of unity.

**Proof:** Let \((U_{\alpha x}, x_{\alpha}, y_{\alpha})\) be a \((F, \Omega_S)\)-chart around \(r_{\alpha}\) which exists due to Lemma 2.1.5 and \(z_{\alpha} := \sqrt{x_{\alpha} - x_{\alpha}(r_{\alpha})}\) be the standard local coordinate on \(\Sigma \cap U_{\alpha}\). We suppose that the parameterization of \(\Sigma \cap U_{\alpha}\) is given by \((x_{\alpha} = z_{\alpha}^2 + a_{\alpha}, y_{\alpha} = z_{\alpha}\psi(z_{\alpha}^2) + \phi(z_{\alpha}^2))\) for some \(\psi\) and \(\phi\) holomorphic on \(\Sigma \cap U_{\alpha}\). We wish to find \(F\) and \(G\) such that the new \((F, \Omega_S)\)-local coordinates \((\tilde{x}_{\alpha}, \tilde{y}_{\alpha})\) given by

\[
\tilde{x}_{\alpha} = F(x_{\alpha}), \quad \tilde{y}_{\alpha} = \frac{y_{\alpha}}{F'(x_{\alpha})} + G'(x_{\alpha})
\]
with the new standard local coordinate \( z_\alpha := \sqrt{x_\alpha - x_\alpha(r_\alpha)} = \sqrt{F(z_\alpha^2 + a) - F(a)} \) satisfies

\[
z_\alpha = F(z_\alpha^2 + a) = \frac{z_\alpha \psi(z_\alpha^2) + \phi(z_\alpha^2)}{F'(z_\alpha^2 + a)} + G'(z_\alpha^2 + a).
\]

This is equivalent to

\[
F^{-1}(0) = a, \quad F'(z_\alpha^2 + F^{-1}(0)) \left( (F(z_\alpha^2 + F^{-1}(0)))^{1/2} - G'(z_\alpha^2 + F^{-1}(0)) \right) = z_\alpha \psi(z_\alpha^2) + \phi(z_\alpha^2). \tag{2.3}
\]

The second equation above can be solved by separately equating the odd and even terms. The odd terms yields:

\[
F'(z_\alpha^2 + F^{-1}(0)) F(z_\alpha^2 + F^{-1}(0))^{1/2} = z_\alpha \psi(z_\alpha^2) \implies \frac{1}{2} \frac{d}{dz_\alpha} \left( (F(z_\alpha^2 + F^{-1}(0)))^{3/2} \right) = z_\alpha^2 \psi(z_\alpha^2). \tag{2.4}
\]

Both sides can be expanded as power series in \( z^2 \), starting with the \( z^2 \) term, so \( F(z^2 + a) \) and hence \( F(x) \) can be found by comparing coefficients. Similarly, we can define \( G(x) := \frac{\phi(x-F^{-1}(0))}{F'(x)} \). Note that if \( (F(z^2 + a))^{1/2} \) satisfies \ref{2.4}, then \( \frac{\phi(x-F^{-1}(0))}{F'(x)} \) also does for any third root of unity \( \xi \).

The tangent space \( T_\Sigma \mathcal{B} \) describes the infinitesimal deformations of the curve \( \Sigma \) inside \( S \). It is isomorphic to the space of global sections of the holomorphic normal bundle \( \nu_\Sigma \cong TS|_\Sigma/T_\Sigma \), where \( TS \) and \( T_\Sigma \) are holomorphic tangent bundles of \( S \) and \( \Sigma \) respectively. In general, given any holomorphic vector bundle \( \mathcal{V} \) on a complex manifold \( X \), we denote the set of holomorphic sections of \( \mathcal{V} \) by \( \Gamma(X, \mathcal{V}) \). The availability of the symplectic form \( \Omega_S \) gives the following result:

**Lemma 2.1.10 (\textit{\textbf{Section 4.2}})** Let \( \Omega^1_S \) be the holomorphic canonical line bundle on \( \Sigma \), then the symplectic form \( \Omega_S \) induces the isomorphism \( \Gamma(\Sigma, \nu_\Sigma) \cong \Gamma(\Sigma, \tilde{\Omega}^1_S) \). Consequently, \( \dim T_\Sigma \mathcal{B} = \dim \Gamma(\Sigma, \tilde{\Omega}^1_S) = g \), hence \( \mathcal{B} \) is \( g \)-dimensional.

**Proof:** We establish the isomorphism \( \Gamma(\Sigma, \nu_\Sigma) \cong \Gamma(\Sigma, \tilde{\Omega}^1_S) \) by \( v \mapsto \Omega_S(v, .)|_\Sigma \). Any holomorphic section of the normal bundle \( v \in \Gamma(\Sigma, TS|_\Sigma/T_\Sigma) \) can be represented as a collection of sections \( \{v_{\alpha \in \sigma} \in \Gamma(V_\alpha, TS)\} \) such that \( v_{\alpha \in \sigma} \in \Gamma(V_\alpha \cap V_{\lambda \in \sigma}, T_{\Sigma}) \) for some open cover \( \{V_{\alpha \in \sigma}\} \) of \( \Sigma \). We note that for each \( \alpha \in \sigma \), \( \Omega_S(v_{\alpha \in \sigma})|_{V_\alpha} \) is a holomorphic form on \( V_\alpha \subset \Sigma \) as it is a pull-back of the contraction between \( \Omega_S \) and \( v_{\alpha \in \sigma} \) which are both holomorphic. Since \( \Omega_S(t, .)|_\Sigma \) for all \( t \in \Gamma(\Sigma, TS) \), we can patch together \( \Omega_S(v_{\alpha \in \sigma})|_{V_\alpha} \) for each \( \alpha \in \sigma \) to get a global section \( \Omega_S(v, .)|_\Sigma \in \Gamma(\Sigma, \tilde{\Omega}^1_S) \).

The map \( v \mapsto \Omega_S(v, .)|_\Sigma \) is injective because if \( \Omega_S(v, .)|_\Sigma = 0 \) then by the fact that \( \Sigma \subset S \) is a Lagrangian submanifold, we have \( v(p) \in T_p \Sigma \) for all \( p \in \Sigma \). Therefore, \( v = 0 \in \Gamma(\Sigma, \nu_\Sigma) \). For surjectivity, given a holomorphic differential form \( \omega \in \Gamma(\Sigma, \Omega^1_S) \), we cover \( \Sigma \) with a collection of \((\mathcal{F}, \Omega_S)\)-charts \( \mathcal{U} = \{U_\alpha \in \Sigma : \mathcal{O}_\alpha \subset \mathcal{O}_\Sigma \} \) such that either \( x_\alpha \) or \( y_\alpha \) is a local coordinate on \( \Sigma \cap U_\alpha \). Let us assume without loss of generality that \( x_\alpha \) is a local coordinate on \( \Sigma \cap U_\alpha \). Then in general \( \omega|_{\Sigma \cap U_\alpha} = \omega_\alpha(x_\alpha)p_{x_\alpha} \) and by taking \( v_p := -\omega_\alpha(x_\alpha)p_{x_\alpha} |_{\Sigma \cap U_\alpha} \in \Gamma(\Sigma \cap U_\alpha, TS|_\Sigma) \) we have \( \Omega_S(v_p)|_{\Sigma \cap U_\alpha} = \omega|_{\Sigma \cap U_\alpha} \). For \( p, p' \in \sigma \) we have on \( U_\alpha \cap U_{\sigma} \) that

\[
\Omega_S(v_p - v_{p'}, .)|_{\Sigma \cap U_\alpha \cap U_{\sigma}} = (\omega|_{\Sigma \cap U_\alpha})|_{\Sigma \cap U_\alpha \cap U_{\sigma}} \neq 0.
\]

Therefore, \( (v_p - v_{p'})|_{\Sigma \cap U_\alpha \cap U_{\sigma}} \in \Gamma(\Sigma \cap U_\alpha \cap U_{\sigma}, TS) \) and \( \{v_p \in \sigma \} \) represents a global section of a normal bundle \( v \in \Gamma(\Sigma, \nu_\Sigma) \) such that \( \Omega_S(v, .)|_\Sigma = \omega \).

Alternatively, since the symplectic form \( \Omega_S \) is a global section of the holomorphic canonical line bundle \( \Omega^1_S \) of \( S \) with no zeros or poles, we have from the adjunction formula: \( \Omega^1_S \cong \Omega^1_S|_\Sigma \otimes \nu_\Sigma \) that \( \Omega^1_S \cong \nu_\Sigma \). It follows that \( \Gamma(\Sigma, \nu_\Sigma) \cong \Gamma(\Sigma, \Omega^1_S) \) and the map \( v \mapsto \Omega_S(v, .) \) explicitly express this isomorphism.

**Definition 2.1.11** Consider the universal family of \( F \)-transversal curves:

\[
Z := \{(\Sigma, p) \in B \times S | p \in \Sigma \} \subseteq B \times S,
\]

let \( \pi : Z \to B \) be the canonical projection and let \( \mathcal{C} \) be a constant sheaf on \( Z \). Then we define the holomorphic symplectic vector bundle \( (\mathcal{H} \to B, \Omega_H, \nabla_{GM}) \) where \( \mathcal{H} := R^1 \pi_* \mathcal{C} \) is a holomorphic vector bundle with fiber over each point \( \Sigma \in B \) given by \( H_\Sigma \cong H^1(\Sigma, \mathcal{C}) \). \( \nabla_{GM} \) is the \textit{\textbf{Gauss-Manin}} connection and the symplectic form \( \Omega_H \) is given by

\[
\Omega_H([\xi_1], [\xi_2]) := \iint_{\Sigma} \xi_1 \land \xi_2 \tag{2.5}
\]

where \( \xi_1, \xi_2 \) are smooth differential forms representing \( [\xi_1], [\xi_2] \in H_\Sigma \).
For any open subset, $B' \subseteq B$ we denote by $\Gamma(B', \mathcal{H})$ the set of holomorphic sections of $\mathcal{H}$ over $U$.

**Remark 2.1.12** The natural symplectic form $\Omega^*_B$ on $H_1(\Sigma, \mathbb{C})$ can be defined using the oriented intersection product of homology classes as follows. For any $[C_1], [C_2] \in H_1(\Sigma, \mathbb{Z})$, the intersection product is given by $[C_1] \cdot [C_2] = [C_1 \cap C_2] \in H_0(\Sigma, \mathbb{Z}) \cong \mathbb{Z}$ which can be extended linearly to the intersection product on $H_1(\Sigma, \mathbb{C}) = H_1(\Sigma, \mathbb{Z}) \otimes \mathbb{C}$. Then, for any $[C_1], [C_2] \in H_1(\Sigma, \mathbb{C})$, we define $\Omega^*_B([C_1], [C_2]) := [C_1] \cdot [C_2]$. Typically, we denote a symplectic basis of $H_1(\Sigma, \mathbb{C})$ by $A$ and $B$ cycles: $\{[A_1], \ldots, [A_g], [B_1], \ldots, [B_g]\}$, $\Omega^*_B([A_1], [A_1]) = \Omega^*_B([B_1], [B_1]) = 0$, $\Omega^*_B([A_1], [B_1]) = \delta_{ij}$.

On $H^1(\Sigma, \mathbb{C})$, the symplectic form $\Omega_B$ is defined as the intersection product of cohomology classes via Poincaré duality $P.D.: H^1(\Sigma, \mathbb{C}) \cong H_1(\Sigma, \mathbb{C})$. In other words, given $\{[\xi_1], [\xi_2]\} \in H^1(\Sigma, \mathbb{C})$ then (2.5) is equivalent to $\Omega_B([\xi_1], [\xi_2]) := \Omega_B(P.D.[\xi_1], P.D.[\xi_2])$. Note also that the expression for $\Omega_B([\xi_1], [\xi_2])$ as given in (2.5) only depends on the cohomology classes of $\xi_1$ and $\xi_2$, because $\int_{\Sigma} f^\ast \xi_1 \wedge f^\ast \xi_2 = \int_{\Sigma} d(f^\ast \xi_1) = 0$ by Stokes Theorem.

**Remark 2.1.13** Suppose that the $A, B$ symplectic basis cycles $\{[A_1], \ldots, [A_g], [B_1], \ldots, [B_g]\}$ of $H_1(\Sigma, \mathbb{C})$ are chosen for $[\Sigma] \in B$. Since $H^1(\Sigma, \mathbb{C}) \cong H_1(\Sigma, \mathbb{C})^\ast$, a cohomology class $[\xi] \in H^1(\Sigma, \mathbb{C})$ is determined by its values on $A$ and $B$ cycles. In particular, the cohomology class $[\xi]$ represented by a closed differential form $\xi$ is given by the $A$ and $B$ periods of $\xi$ and we identify $\mathcal{H}_C = H^1(\Sigma, \mathbb{C}) \cong \mathbb{C}^{2g}$ by $H^1(\Sigma, \mathbb{C}) \ni [\xi] \mapsto \left(\int_{A_1} \xi, \ldots, \int_{A_g} \xi, \int_{B_1} \xi, \ldots, \int_{B_g} \xi\right) \in \mathbb{C}^{2g}$.

It can happen as we move from $[\Sigma]$ along some closed path in $B$, letting $A, B$ cycles deform continuously, that once we return to the point $[\Sigma]$ the $A, B$ cycles differ from the original by some Dehn twist actions. On the other hand, given a sufficiently small open neighbourhood $B_{\Sigma} \subseteq B$, we will be able to choose $A, B$ symplectic basis cycles consistently throughout $B_{\Sigma}$. The Gauss-Manin connection $\nabla_{GM}$ can be described locally on $B_{\Sigma}$ as the identification of any two cohomology classes on two different fibers $\{[\xi]\} \in H_{1, \Sigma}(\mathbb{C}), [\xi] \in H_{1, \Sigma}(\mathbb{C})$, if they have the same $A$ and $B$ periods: $\int_{A_k \subset \Sigma} \xi_1 = \int_{A_k \subset \Sigma} \xi_2 = \int_{B_k \subset \Sigma} \xi_1 = \int_{B_k \subset \Sigma} \xi_2$. This gives a local trivialization $\mathcal{H}_{B_{\Sigma}} \cong \mathbb{C}^{2g} \times B_{\Sigma}$, verifying that $\mathcal{H}$ is a vector bundle.

The following gives an alternative expression for $\Omega_B$:  

**Lemma 2.1.14 (Riemann bilinear identity)** Let $[\xi_1], [\xi_2] \in H^1(\Sigma, \mathbb{C})$ then

$$
\int_{\Sigma} \xi_1 \wedge \xi_2 = \frac{1}{2\pi i} \sum_{k=1}^g \left( \int_{A_k} \xi_2 \int_{B_k} \xi_1 - \int_{B_k} \xi_2 \int_{A_k} \xi_1 \right)
$$

where $\xi_1, \xi_2$ are smooth differential forms representing $[\xi_1], [\xi_2]$.

**Proof:** First, we show that for any $[\xi] \in H^1(\Sigma, \mathbb{C})$ has a representative $\xi = \alpha + \beta$ where $\alpha$ is holomorphic $(\partial \alpha = 0)$ and $\beta$ is anti-holomorphic $(\partial \beta = 0)$. A smooth differential form $\xi'$ representing $[\xi]$ can be decomposed as $\xi' = \alpha' + \beta'$ where $\alpha'$ is a smooth (1,0)-form and $\beta'$ is a smooth (0,1)-form. Then $d\xi' = \partial \beta' - \partial \alpha' = 0$ implies $\partial \alpha' = -\partial \beta'$. Since Riemann surfaces are examples of Kähler manifolds, $\partial\partial$-Lemma [38] Proposition 6.17 tells us that there exists a smooth function $f$ such that $\partial \alpha' + \partial \beta' = -\partial \beta'$. We can see that $\xi := \xi' + df = \alpha + \beta$ where $\alpha := \alpha' + \partial f$ and $\beta = \beta' + \partial f$ is the desired representative.

The rest of the proof follows from Stokes’ theorem and the standard argument leading to the Riemann bilinear identity. For example, we have

$$
\int_{\Delta} \alpha \wedge \beta = \int_{\Delta} d\phi \wedge \beta = \int_{\Delta} d(\phi \beta) = \int_{\Delta} d(\phi \beta) = \frac{1}{2\pi i} \sum_{k=1}^g \left( \int_{A_k} \beta \int_{B_k} \alpha - \int_{B_k} \beta \int_{A_k} \alpha \right)
$$

where $\Delta := \Sigma \cup \cup_{k=1}^g (A_k \cup B_k)$ is a simply-connected domain and $\alpha = df = \partial f$ for some holomorphic function $\phi$ on $\Delta$ by Poincaré Lemma.

Let us fix a reference point $[\Sigma_0] \in B$ and an open neighbourhood $B_{\Sigma_0} \subseteq B$ of $[\Sigma_0]$. Later we will explain more precisely how $B_{\Sigma_0}$ is selected (see Condition 2.5.2). But for now, we simply require $B_{\Sigma_0}$ to be contractible and sufficiently small such that it can be covered by a single coordinate chart $(B_{\Sigma_0}, u^1, \ldots, u^g)$. We will denote by $\mathcal{H} \to B_{\Sigma_0}$ the vector bundle given by the restriction of $\mathcal{H}$ to $B_{\Sigma_0}$, which is trivial because $B_{\Sigma_0}$ is contractible. Let
Let us discuss the first map $T|Σ|B_{Σ_n} \xrightarrow{\cong} \Gamma(Σ, TS|Σ/TΣ)$. We map $v = \sum_{k=1}^{q} v^k \frac{\partial}{\partial u^k}$ to a global normal vector field $n_v \in \Gamma(Σ, TS|Σ/TΣ)$ which can be defined in terms of $TS|Σ$-sections on each $(F, Ω_S)$-chart $(U_p, x_p, y_p)$:

$$n_v|Σ∩U_p := \sum_{k=1}^{q} v^k \left( \frac{\partial x_p}{\partial u^k} \frac{\partial}{\partial x_p} + \frac{\partial y_p}{\partial u^k} \frac{\partial}{\partial y_p} \right) \in \Gamma(Σ ∩ U_p, TS|Σ).$$

(2.6)

Taking the quotient of $n_v|Σ∩U_p$ on each $(U_p, x_p, y_p)$ and patch each of them together, we get a global section $n_v$. Finally, we define $\phi_v : [Σ] \to H_Σ$ where $\phi_v : Ω_v := Ω_S(n_v, ...) \in \Gamma(Σ, Ω_Σ)$.

$$n_v|Σ∩U_p := \sum_{k=1}^{q} Ω_S(n_vu, ...)|Σ|du^k \in T|Σ|B ∩ Γ(Σ, Ω_Σ), \quad \phi_v := [Ω_v] := \sum_{k=1}^{q} |Ω_v(n_vu, ...)|Σ|du^k \in T|Σ|B ∩ H_Σ.$$  

(2.7)

Remark 2.1.15 The image $\text{im}\phi_v = Γ(Σ, Ω_Σ)$ is a Lagrangian subspace of $H_Σ$ for every $[Σ] \in B_{Σ_n}$.

At first glance, the expression (2.6) seems ambiguous because it depends on the choice of a connection, in other words, on the derivatives of $x_p$ and $y_p$ are taken with respect to $u^k$. Suppose that $Σ ∩ U_p = \{ (x_p, y_p) ∈ U_p \mid P_p(x_p, y_p; u) = 0 \}$ for some polynomial $P_p$. For any $q ∈ Σ ∩ U_p$, we have $t ∈ T_q Σ ⊂ T_q S$ if $t dP_p = 0$ where $dP_p = \frac{\partial P_p}{\partial x_p} dx_p + \frac{\partial P_p}{\partial y_p} dy_p$. The variation of the curve $Σ$ in the $u^k$-direction in $B$ gives

$$\frac{\partial P_p}{\partial u^k} + \frac{\partial P_p}{\partial x_p} \frac{\partial x_p}{\partial u^k} + \frac{\partial P_p}{\partial y_p} \frac{\partial y_p}{\partial u^k} = 0.$$  

(2.8)

Choosing a connection is equivalent to choosing $\frac{\partial x_p}{\partial u^k}$ and $\frac{\partial y_p}{\partial u^k}$ satisfying this equation. We need to check that if connections are chosen differently on each $(U_p, x_p, y_p)$ then

$$(v_u|Σ∩U_p)|Σ∩U_i∩U_j - (v_u|Σ∩U_j)|Σ∩U_i∩U_j \in Γ(Σ ∩ U_i ∩ U_j, TΣ)$$

and therefore we can patch the quotient of each $v_u|Σ∩U_p$ to form a global section $n_v \in Γ(Σ, n_Σ)$. The following lemma resolves this concern:

Lemma 2.1.16 Suppose we obtain $(n_v|Σ∩U_{p_i})_i, i = 1, 2$ using any two different choices of connections, then $(n_v|Σ∩U_{p_i})_1 - (n_v|Σ∩U_{p_i})_2 \in Γ(Σ ∩ U_i, TΣ)$.

Proof: Without loss of generality, let us assume that $v = \frac{\partial}{\partial u^k}$. For $i = 1, 2$, let

$$(n_v|Σ∩U_p)_i := \left( \frac{\partial x_p}{\partial u^k} \frac{\partial}{\partial x_p} + \frac{\partial y_p}{\partial u^k} \frac{\partial}{\partial y_p} \right)_i$$

where

$$\frac{\partial P_p}{\partial u^k} + \frac{\partial P_p}{\partial x_p} \frac{\partial x_p}{\partial u^k} + \frac{\partial P_p}{\partial y_p} \frac{\partial y_p}{\partial u^k} = 0.$$  

(2.9)

If we subtract (2.9) with $i = 2$ from (2.9) with $i = 1$ then

$$\left( \left( \frac{\partial x_p}{\partial u^k} \right)_1 - \left( \frac{\partial x_p}{\partial u^k} \right)_2 \right) \frac{\partial P_p}{\partial x_p} + \left( \left( \frac{\partial y_p}{\partial u^k} \right)_1 - \left( \frac{\partial y_p}{\partial u^k} \right)_2 \right) \frac{\partial P_p}{\partial y_p} = 0.$$

The next lemma tells us that $\nabla_{GM}[ξ] = \sum_{k=1}^{q} \left[ \frac{\partial}{\partial u^k} \right] du^k$ is independent of the choice of the connection and the differential form $ξ$ we choose to represent $[ξ]$.
Lemma 2.1.17 Let ξ_Σ be a holomorphic family of meromorphic differential forms defined for each [Σ] ∈ B_{Σ₀} on an open subsets D_Σ ⊆ Σ and let (\frac{∂ξ_Σ}{∂u^i})_i, i = 1, 2 be the derivative \frac{∂}{∂u^i} taken using two different choices of connections. Then (\frac{∂ξ_Σ}{∂u^i}) - (\frac{∂ξ_Σ}{∂u^i})_2 is an exact meromorphic differential on D_Σ. In particular, for any closed contour C ⊆ D_Σ which deforms homotopically over B_{Σ₀} and avoiding all poles of ξ_Σ for each [Σ] ∈ B_{Σ₀}, we have
\[
\frac{∂}{∂u^k} \oint_C ξ_Σ = \oint_C \left( \frac{∂}{∂u^k} ξ_Σ \right)_∇
\]
(2.10)

independent of the the choice of connection ∇ the derivative \frac{∂}{∂u^k}ξ_Σ is taken with respect to.

Proof: First, let us consider the case in which D_Σ ⊆ Σ ∩ U_p where (U_p,x_p,y_p) is a (F,Ω_Σ)-chart with dx_p|_{ΣU_p} ≠ 0. We write in general ξ_Σ|_{Σ ∩ U_p} = ξ_Σ,p(x_p,u)dx_p. Then we have for i = 1, 2:
\[
\left( \frac{∂ξ_Σ}{∂u^k} \right)_{i} = \frac{∂ξ_Σ}{∂u^k}dx_p + \left( \frac{∂ξ_Σ}{∂u^k} \right)_{i}dx_p + ξ_Σ,pd\left( \frac{∂ξ_Σ}{∂u^k} \right)_{i}
\]
\[
\frac{∂ξ_Σ,p}{∂u^k}dx_p + \left( \frac{∂ξ_Σ,p}{∂u^k} \right)_{i}dx_p + \left( \frac{∂ξ_Σ,p}{∂u^k} \right)_{i}dξ_p + d\left( ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{i} \right) = \frac{∂ξ_Σ,p}{∂u^k}dx_p + d\left( ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{i} \right).
\]

Evidently, we have
\[
\left( \frac{∂ξ_Σ}{∂u^k} \right) - \left( \frac{∂ξ_Σ}{∂u^k} \right)_{2} = d\left( ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{1} - ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{2} \right)
\]
which is exact as claimed. In general we cover D_Σ with a collection of (F,Ω_Σ)-charts \{(U_p∈ς, x_p∈ς, y_p∈ς)\} and check that the function ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{1} - ξ_Σ,p \left( \frac{∂ξ_Σ}{∂u^k} \right)_{2} on each Σ ∩ U_p patches together to give us a function Ξ_{Σ,12} defined on D_Σ such that dΞ_{Σ,12} = \left( \frac{∂ξ_Σ}{∂u^k} \right)_{1} - \left( \frac{∂ξ_Σ}{∂u^k} \right)_{2}.

To see that (2.10) is true, we dissect C into closed segments C_i, i = 1, ⋯, N such that C_i ⊆ Σ ∩ U_p, then apply the Leibniz integral rule on each segment C_i. Since the endpoints of each C_i vary with u^k we also get the boundary term contribution, but the sum of these contributions from each C_i will be zero because C is closed. Note that there is no ambiguity in what connection to use on the right-hand-side of (2.10) because the result will only be differed by an exact differential, which vanishes on a closed contour C. □

Lemma 2.1.18 ([25], Section 5.1) The symplectic vector bundle (H → B, Ω_H, dΩ_GM) is flat and Ω_H is dΩ_GM-covariantly constant.

Proof: Let dΩ_GM : Γ(B_{Σ₀},Ω_B ⊗ H) → Γ(B_{Σ₀},Ω_B ⊗ H) be the exterior covariant derivative. The condition that dΩ_GM is flat is the same as the vanishing of the curvature tensor R_GM = dΩ_GM ○ dΩ_GM = 0. For ψ = s[Σ] ∈ Γ(B_{Σ₀},Ω_B ⊗ H), s ∈ Γ(B_{Σ₀},Ω_B) and [Σ] ∈ Γ(B_{Σ₀},H), we have
\[
dΩ_GM ψ = (ds)[Σ] + (-1)^r s ∧ dΩ_GM [Σ] = (ds)[Σ] + (-1)^r s ∧ \sum_{k=1}^{g} \left[ \frac{∂ξ_Σ}{∂u^k} \right] du^k
\]
where we have used Lemma 2.1.17 Ω_GM [Σ] = \sum_{k=1}^{g} \left[ \frac{∂ξ_Σ}{∂u^k} \right] du^k. Therefore,
\[
d^2Ω_GM ψ = (d^2s)[Σ] + (-1)^r (ds) ∧ \sum_{k=1}^{g} \left[ \frac{∂ξ_Σ}{∂u^k} \right] du^k
\]
\[+ (-1)^{r+1} (ds) ∧ \sum_{k=1}^{g} \left[ \frac{∂ξ_Σ}{∂u^k} \right] du^k + (-1)^r s ∧ \sum_{k,l=1}^{g} \left[ \frac{∂ξ_Σ}{∂u^k∂u^l} \right] du^k ∧ du^l = 0
\]
which means Ω_GM is a flat connection.

Because the vector bundle H → B is flat, parallel transport on H → B_{Σ₀} using the Gauss-Manin connection is path-independent. Let us denote by Γ(Σ_0)[Σ] ∈ H_Σ the parallel transport of [Σ] ∈ H_Σ from the point [Σ] ∈ B_{Σ₀} to [Σ'] ∈ B_{Σ₀}. Since parallel transport preserves A and B-periods, we have Ω_H(Γ(Σ_0)[η_1], Γ(Σ_0)[η_2]) = Ω_H([η_1], [η_2]) proving that Ω_H is Ω_GM-covariantly constant.

We will find in Section 2.3 that the connection given by taking derivatives keeping the direction of foliation leaves constant is particularly important and we denote it by dF. Let us write down φ_Σ(v) and φ_Σ(v) using
\( \nabla_F \). Let us cover \( \Sigma \) with a collection of \((F, \Omega_S)\)-charts \( \mathcal{U} = \{(U_p, x \in \sigma, y_p \in \sigma)\} \). On each \( \Sigma \cap U_p \), we write \( \nabla_F = \sum_{k,l=1}^g du_k \frac{\partial}{\partial y^k} |_{x_p = \text{const}} \). Straightforwardly, we have

\[
\phi_{\Sigma}|_{\Sigma \cap U_p} = \sum_{k=1}^g \Omega_S(n_{v_k,1}|_{x_p = \text{const}}) du_k = \sum_{k=1}^g \Omega_S \left( \frac{\partial y_p}{\partial u^k} |_{x_p = \text{const}} \frac{\partial}{\partial u^k} \right) |_{\Sigma \cap U_p} du_k
\]

and so \( \phi_{\Sigma}(v)|_{\Sigma \cap U_p} = -d\nabla_F(y_p dx|_{\Sigma \cap U_p}) \). Lastly, we simply put \( \phi_{\Sigma}(v) = [\phi_{\Sigma}(v)] \in \mathcal{H}_\Sigma \).

**Remark 2.1.19** Note that, from (2.8) we have \( \partial y_p/\partial u^k |_{x_p = \text{const}} \) vanishes with order 1 zero exactly at ramification points because \( dx_p |_{\Sigma \cap U_p} \) does. Suppose that \( \Sigma \cap U_p \) contains a ramification point \( r_\alpha \), then \( \partial y_p/\partial u^k |_{x_p = \text{const}} \) has a simple pole at \( r_\alpha \). However, \( \partial y_p/\partial u^k |_{x_p = \text{const}} dx_p |_{\Sigma \cap U_p} \) remains finite at \( r_\alpha \) because the simple pole cancels out with the simple zero of \( dx_p |_{\Sigma \cap U_p} \).

From this analysis, we conclude that \( \phi_{\Sigma}(v) \) is holomorphic on \( \Sigma \), i.e. \( \phi_{\Sigma}(v) \in \Gamma(\Sigma, \Omega_S^1) \), as expected since the definition of \( \phi_{\Sigma} \) is independent of our choice of the connection (see Lemma 2.1.16). We refer to the proof of Lemma 2.5.35 for a version of this argument repeated using the standard local coordinate \( z_\alpha \).

Let us compute the exterior covariant derivative of \( \phi_{\Sigma} \) using \( \nabla_F \), we have

\[
d_{\nabla_F} \phi_{\Sigma}|_{\Sigma \cap U_p} = d_{\nabla_F} \left( \sum_{k=1}^g \Omega_S(n_{v_k,1}|_{x_p = \text{const}}) du_k \right) |_{\Sigma \cap U_p} = d_{\nabla_F} \left( -d\nabla_F(y_p dx|_{\Sigma \cap U_p}) \right)
\]

for any \((F, \Omega_S)\)-chart \((U_p, x_p, y_p) \in \mathcal{U} \). This means \( \nabla_F \phi_{\Sigma} = 0 \) and therefore,

\[
d_{\nabla_{GM}} \phi_{\Sigma} = d_{\nabla_{GM}} [\phi_{\Sigma}] = [d_{\nabla_F} \phi_{\Sigma}] = 0,
\]

where we have applied Lemma 2.1.17 at the second equality. Since \( \mathcal{B}_{\Sigma_0} \) is contractible, by the Poincaré Lemma (see Lemma 2.1.23 below), \( d_{\nabla_{GM}} \phi = 0 \) on \( \mathcal{B}_{\Sigma_0} \) implies that there exists

\[
\theta \in \Gamma(\mathcal{B}_{\Sigma_0}, \mathcal{H}) \text{ such that } d_{\nabla_{GM}} \theta = \phi. \tag{2.11}
\]

### 2.1.3 The embedding of \( \mathcal{B}_{\Sigma_0} \) into \( \mathcal{H}_{\Sigma_0} \) as a Lagrangian submanifold

Let us consider the map \( \Phi_{\Sigma_0} \), embedding the neighbourhood \( \mathcal{B}_{\Sigma_0} \subseteq \mathcal{B} \) into a fiber \( \mathcal{H}_{\Sigma_0} \) at \([\Sigma_0] \in \mathcal{B}_{\Sigma_0} \). Following [25], we first define the affine connection \( \nabla_{GM} + \phi \) on \( \mathcal{H} \):

\[
(\nabla_{GM} + \phi)[\xi] := \nabla_{GM}[\xi] + \phi
\]

for any section \([\xi] \in \Gamma(\mathcal{B}_{\Sigma_0}, \mathcal{H}) \). The map \( \Phi_{\Sigma_0} : \mathcal{B}_{\Sigma_0} \to \mathcal{H}_{\Sigma_0} \) is defined by sending a point \([\Sigma] \in \mathcal{B}_{\Sigma_0} \) to the image of the zero vector \( 0_{\Sigma} \in \mathcal{H}_{\Sigma_0} \) under the parallel transport from point \([\Sigma_0] \) to \([\Sigma] \) using the affine connection \( \nabla_{GM} + \phi \). In general, given \([\Sigma], [\Sigma_1] \in \mathcal{B}_{\Sigma_0} \), the parallel transport of \( 0_{\Sigma_1} \in \mathcal{H}_{\Sigma_1} \) to \( \mathcal{H}_{\Sigma_0} \) is unique, path-independent and it is given by

\[
u_{\Sigma_1}(\Sigma) := -\theta_\Sigma + \Gamma_{[\Sigma_1]}^{[\Sigma]} \theta_{\Sigma_1}.
\]

It follows that

\[
\Phi_{\Sigma_0}(\Sigma) := \nu_{\Sigma}(\Sigma_0) = -\theta_{\Sigma_0} + \Gamma_{[\Sigma]}^{[\Sigma_0]} \theta_{\Sigma}.
\]

We denote the image of \( \Phi_{\Sigma_0} \) by

\[
\mathcal{L}_{\Sigma_0} := \text{im} \Phi_{\Sigma_0} \subset \mathcal{H}_{\Sigma_0}.
\]
Let \( v = \sum_{k=1}^{g} v^k \frac{\partial}{\partial u^k} \in T_{[\Sigma]} B_{\Sigma_0} \) be any tangent vector, then

\[
\iota_v \phi_{\Sigma_0}(\Sigma) = \sum_{k=1}^{g} v^k \frac{\partial \phi_{\Sigma_0}(\Sigma)}{\partial u^k} = \Gamma^{[\Sigma]}_{\Sigma} \text{ and } \nabla_{GM} \phi_{\Sigma} = \Gamma^{[\Sigma]}_{\Sigma} \iota_v \phi_{\Sigma}
\]

is a tangent vector to \( L_{\Sigma_0} \subset H_{\Sigma_0} \). Since \( v \mapsto \iota_v \phi_{\Sigma_0} \) is injective because \( \phi_{\Sigma} \) is injective, by assuming that \( B_{\Sigma_0} \) is small enough we have that \( \Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow H_{\Sigma_0} \) is a embeds \( B_{\Sigma_0} \) as a submanifold in \( H_{\Sigma_0} \).

**Lemma 2.1.20** ([25], Section 5.1) \( L_{\Sigma_0} \) is a Lagrangian submanifold of \( H_{\Sigma_0} \)

**Proof:** Since \( H_{\Sigma_0} = H^1(\Sigma, \mathbb{C}) \) is \( \mathbb{C}^{2g} \) and \( \dim L_{\Sigma_0} = \dim B_{\Sigma_0} = \frac{1}{2} \dim H_{\Sigma_0} \) it remains for us to check that \( \Omega_H|_{L_{\Sigma_0}} = 0 \). For \( v_i \in T_{[\Sigma]} B_{\Sigma_0}, i = 1, 2 \) we have \( \iota_{v_i} \phi_{\Sigma_0} \in T_{\Phi_{\Sigma_0}(\Sigma)} L_{\Sigma_0} \) and

\[
\Omega_H(v_i \iota_{v_i} \phi_{\Sigma_0}) = \Omega_H(\Gamma^{[\Sigma]}_{\Sigma} \iota_{v_i} \phi_{\Sigma}, \Gamma^{[\Sigma]}_{\Sigma} \iota_{v_i} \phi_{\Sigma}) = \Omega_H(\iota_{v_i} \phi_{\Sigma}, \iota_{v_i} \phi_{\Sigma}) = 0
\]

because the image \( \text{im}\phi_{\Sigma} = \Gamma(\Sigma, \Omega^1_{\Sigma}) \) is a Lagrangian subspace of \( H_{\Sigma} \).

Let us consider a trivialization of \( \mathcal{H} \rightarrow B_{\Sigma_0} \) by choosing \( A, B \)-symplectic basis cycles of \( H_{\Sigma, \mathbb{C}} \) for each \( [\Sigma] \in B_{\Sigma_0} \) and identify \( H_{\Sigma} \cong \mathbb{C}^{2g} \) as in Remark 2.1.13: \( [\Sigma] \mapsto (\tilde{f}_A, \xi, \tilde{f}_B, \xi, \tilde{b}_A, \xi, \tilde{b}_B, \xi) \in \mathbb{C}^{2g} \). Let us define

\[
a^i(\Sigma) := \tilde{f}_A, \quad b_i(\Sigma) := \tilde{b}_B, \quad i = 1, ..., g.
\]

We will often write \( a^i(\Sigma) \) and \( b_i(\Sigma) \) simply as \( a^i \) and \( b_i \) when they do not cause any ambiguity.

**Lemma 2.1.21** \( \{a^1, ..., a^g\} \) is a coordinate system for \( B_{\Sigma_0} \).

**Proof:** The matrix \( \left( \frac{\partial a^i}{\partial u^j} \right) \) is invertible because \( \frac{\partial a^i}{\partial u^j} \equiv \frac{\partial a^j}{\partial u^i} \tilde{f}_A, \xi = \tilde{f}_A, \iota \frac{\partial}{\partial x^j} \nabla_{GM} \phi_{\Sigma} = \tilde{f}_A, \iota \frac{\partial}{\partial x^i} \phi_{\Sigma} \). So if there exists \( (v^i) \in \mathbb{C}^g \) such that \( \sum_{j=1}^{g} v^i \frac{\partial a^j}{\partial u^i} = 0, i = 1, ..., g \) then \( \phi_{\Sigma}(v) = \sum_{j=1}^{g} v^i \frac{\partial a^j}{\partial u^i} \phi_{\Sigma} = 0 \). But we know that \( v \mapsto \iota_v \phi_{\Sigma} \) is injective, therefore \( v = 0 \). Hence \( a^i := a^i(u^1, ..., u^g), i = 1, ..., g \) is a holomorphic coordinates transformation.

So \( b_i \) can be written as a function of \( \{a^1, ..., a^g\} \). We can write \( \Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow H_{\Sigma_0} \) using this trivialization as

\[
[\Sigma] := (a^1(\Sigma), ..., a^g(\Sigma)) \mapsto \Phi(\Sigma) = (a^1(\Sigma) - a^1(\Sigma_0), ..., a^g(\Sigma) - a^g(\Sigma_0), b^1(\Sigma) - b^1(\Sigma_0), ..., b^g(\Sigma) - b^g(\Sigma_0))
\]

and

\[
\frac{\partial \Phi_{\Sigma_0}(\Sigma)}{\partial a^i} = \left( \begin{array}{cccc}
0, & \ldots, & 0, & \frac{\partial b_1}{\partial a_i} \ldots, \frac{\partial b_g}{\partial a_i}
\end{array} \right) \in T_{\Phi_{\Sigma_0}(\Sigma)} \text{im}\phi_{\Sigma_0}, \quad i = 1, ..., g.
\]

It follows from Lemma 2.1.20 that for any \( i, j = 1, ..., g \) we have

\[
0 = \Omega_H \left( \frac{\partial \Phi_{\Sigma_0}(\Sigma)}{\partial a^i}, \frac{\partial \Phi_{\Sigma_0}(\Sigma)}{\partial a^j} \right) = \frac{\partial b_j}{\partial a^i} - \frac{\partial b_i}{\partial a^j}.
\]

Therefore, by an application of Poincaré lemma, there exists a holomorphic function \( \tilde{\mathcal{S}}_{\Sigma_0} = \tilde{\mathcal{S}}_{\Sigma_0}(a^1, ..., a^g) \) on \( B_{\Sigma_0} \) such that

\[
b_i = \frac{\partial \tilde{\mathcal{S}}_{\Sigma_0}(a^1, ..., a^g)}{\partial a^i}, \quad i = 1, ..., g.
\]

(2.12)

The section \( \theta \in \Gamma(B_{\Sigma_0}, \mathcal{H}) \) is uniquely determined up to an addition of a parallel section \( c \in \Gamma(B_{\Sigma_0}, \mathcal{H}), \nabla_{GM} c = 0 \). Therefore, given the moduli space \( \mathcal{B} \) of \( \mathcal{F} \)-transversal curves, the function \( \tilde{\mathcal{S}}_{\Sigma_0} \) is unique up to an addition of a linear term.

**Definition 2.1.22** Given the moduli space \( \mathcal{B} \) of \( \mathcal{F} \)-transversal curves inside a foliated symplectic surface \( (S, \Omega_S, \mathcal{F}) \), the prepotential \( \mathfrak{S}_{\Sigma_0} = \mathfrak{S}_{\Sigma_0}(a^1, ..., a^g) \) is a holomorphic function locally defined on the open neighbourhood \( B_{\Sigma_0} \ni [\Sigma_0] \) which relates \( A \) and \( B \)-periods of \( \theta_{\Sigma} \in H_{\Sigma} \) according to (2.12).

The prepotential is the generating function of the Lagrangian submanifold \( L_{\Sigma_0} := \text{im}\Phi_{\Sigma_0} \subset H_{\Sigma_0} \). In other words, the prepotential \( \mathfrak{S}_{\Sigma_0} \) naturally arises from the study of the deformation of curves \( \Sigma \) embedded in a foliated symplectic surface \( (S, \Omega_S, \mathcal{F}) \) around some neighbourhood \( B_{\Sigma_0} \) of \( [\Sigma_0] \) in the moduli space \( \mathcal{B} \).
2.1.4 Generalization

Previously, we considered a particular vector bundle $\mathcal{H} \to \mathcal{B}$ and an embedding of a neighbourhood $\mathcal{B}_{\Sigma_0}$ of $[\Sigma_0] \in \mathcal{B}$ into a fiber $\mathcal{H}_{\Sigma_0}$ using the affine connection $\nabla_{\Omega M} + \phi$. We showed that the image is a Lagrangian submanifold. This type of embedding can be done with a more general class of symplectic vector bundles.

Let us end this section by giving a discussion of the general setting. First, let us state and proof a version of Poincaré Lemma for holomorphic flat vector bundles:

**Lemma 2.1.23** Let $(\mathcal{E} \to X, \nabla)$ be a $n$-dimensional holomorphic vector bundle over a contractible $m$-dimensional complex manifold $X$ with a flat connection $\nabla$ and let $d\nabla : \Omega^X_X \otimes \mathcal{E} \to \Omega^{X+1}_X \otimes \mathcal{E}$ be the corresponding exterior covariant derivative. Then given a section $\xi \in \Gamma(X, \Omega^{X+1}_X \otimes \mathcal{E})$ such that $d\nabla \xi = 0$, there exists a section $\eta \in \Gamma(X, \Omega^X_X \otimes \mathcal{E})$ such that $\xi = d\nabla \eta$.

**Proof:** Let us pick a basis $\{e_i\}$ of $\mathcal{E}_{x_0}$ at some point $x_0 \in X$ and let the section $e_i \in \Gamma(X, \mathcal{E})$ be given at any $x \in X$ by $e_i = e_i \otimes e_i$, where $\Gamma^e_{x_0}$ is the parallel transport on $\mathcal{E}_{x_0}$ to $x$ using the flat connection $\nabla$. Since $\mathcal{E} \to X$ is flat, the parallel transport with respect to the connection $\nabla$ is path-independent. On the other hand, the existence and uniqueness of the parallel transport of $e_i$ from $x_0$ to $x$ along any path follows from Picard–Lindelöf theorem. It follows that $e_i(x) := \Gamma^e_{x_0} x_0 e_i \in \mathcal{E}_x$ is well-defined for $x \in X$. Therefore, we have parallel sections $\nabla e_i \in \Gamma(X, \mathcal{E})$, $\nabla e_i = 0$, and $\{e_i\}$ is a basis of the fiber $\mathcal{E}_x$ for all $x \in X$. A section $\xi \in \Gamma(X, \Omega^{X+1}_X \otimes \mathcal{E})$ can be expressed using the local coordinates $\{x^1, \ldots, x^n\}$ of $X$ as $\xi := \sum_{k=1}^{n} \xi_k e_k$ where $\xi_k := \sum_{i=1}^{m} \xi_{i1 \cdots i_k} x^1 \wedge \cdots \wedge x^n \in \Gamma(X, \Omega^X_X)$. Using $\nabla e_k = 0$, we have that

$$d\nabla \xi = \sum_{k=1}^{n} \left( (d\xi_k) e_k + (-1)^i \xi_k \wedge \nabla e_k \right) = \sum_{k=1}^{n} (d\xi_k) e_k.$$

Consequently, if $d\nabla \xi = 0$ then $d\xi_k = 0$ for all $k = 1, \ldots, n$. Since $X$ is contractible, we can apply the usual Poincaré Lemma for differential forms to $\xi$ and conclude that there exists $\eta_k \in \Gamma(X, \Omega^{X-1}_X)$ such that $d\eta_k = \xi_k$.

It is now a matter of simple calculation to verify that $d\nabla \eta = \xi$ where $\eta := \sum_{k=1}^{n} \eta_k e_k$. \hfill \Box

Let us now present the general version of the embedding $\mathcal{B}_{\Sigma_0} \to \mathcal{H}_{\Sigma_0}$:

**Proposition 2.1.24** Let $(\mathcal{E} \to X, \Omega^X, \nabla, \phi)$ be a $2n$-dimensional holomorphic symplectic vector bundle over a $n$-dimensional complex manifold $X$ with a flat connection $\nabla$, a $\nabla$-covariantly constant symplectic form $\Omega^X$ and $\phi \in \Gamma(X, \Omega^{X-1}_X \otimes \mathcal{E})$, $d\nabla \phi = 0$ such that for each $x \in X$, $\phi_x : T_x X \to \mathcal{E}_x$ embeds $T_x X$ as a Lagrangian subspace of $\mathcal{E}_x$. Fix a reference point $x_0 \in X$. There exists an open neighbourhood $X_{x_0} \subseteq X$ of $x_0$ such that the map $\Phi_{x_0} : X_{x_0} \to \mathcal{E}_{x_0}$, given by sending $x \in X_{x_0}$ to the image of $0 \in \mathcal{E}_x$ under the parallel transport from $x$ to $x_0$ using the affine connection $\nabla + \phi$ is a well-defined embedding of $X_{x_0}$ into a Lagrangian submanifold $\mathcal{L}_{x_0} := \im \Phi_{x_0} \subseteq \mathcal{E}_{x_0}$.

**Proof:** Let $X_{x_0} \subseteq X$ be a contractible open neighbourhood of $x_0 \in X$. Since $d\nabla \phi = 0$, by Lemma 2.1.23 there exists a section $\theta \in \Gamma(X, \Omega^X_X)$ such that $d\nabla \theta = \nabla \theta = \phi$. For $x \in X_{x_0}$, the section $v_x \in \Gamma(X_{x_0}, \mathcal{E})$, $v_x(x) := -\theta_x + \Gamma^e_{x_0} x_0 \theta_x$ satisfies $v_x(x_1) = 0$ and $\nabla v_x(x) = \phi_x$. For all $x_1, x \in X_{x_0}$, the parallel transport of $0 \in \mathcal{E}_{x_1}$ to $\mathcal{E}_x$ using the affine connection $\nabla + \phi$ is path-independent and it is uniquely given by $v_x(x)$. Therefore, the map $\Phi_{x_0} : X_{x_0} \to \mathcal{E}_{x_0}$ is given by

$$\Phi_{x_0}(x) := v_x(x_0) = -\theta_x + \Gamma^e_{x_0} x_0 \theta_x.$$

Let us compute the derivatives of $\Phi_{x_0}$. Suppose that we can cover $X_{x_0}$ with a single coordinates chart $(X_{x_0}, x^1, \ldots, x^n)$ then

$$d\Phi_{x_0}(x) = \sum_{i=1}^{n} dx^i \frac{\partial \Phi_{x_0}(x)}{\partial x^i} = \sum_{i=1}^{n} dx^i \frac{\partial}{\partial x^i} \sum_{k=1}^{n} \theta_k(x) e_k(x) = \sum_{i=1}^{n} dx^i \frac{\partial}{\partial x^i} \sum_{k=1}^{n} \theta_k(x) e_k(x) = \Gamma^e_{x_0} x_0 \phi_x.$$

For every $v \in T_x X_{x_0}$, we have $\iota_v d\Phi_{x_0}(x) = \iota_v d\Phi_{x_0}(x)$, $\iota_v d\Phi_{x_0}(x) = \Omega^e_{x_0} x_0 \phi_x = \iota_v \phi_x = 0$ by the assumption that $\phi_x$ embeds $T_x X$ as a Lagrangian subspace of $\mathcal{E}_x$. Since $\phi_x$ is injective, the rank of $d\Phi_{x_0}(x)$ is $n$ for all $x \in X_{x_0}$. It follows that $\dim \mathcal{L}_{x_0} = \frac{1}{2} \dim \mathcal{E}_{x_0}$, hence $\mathcal{L}_{x_0} \subseteq \mathcal{E}_{x_0}$ is a Lagrangian submanifold. \hfill \Box
The proof of Proposition [2.1.24] only works when \( E \to X \) is finite-dimensional, hence the result need not hold when the dimension is infinite. Nevertheless, Proposition [2.1.24] gives us a guideline of what to expect when we consider the analogous embedding in the infinite-dimensional case. We will see this in Section [2.3] where we consider the infinite-dimensional vector bundle \( W, M \to Discs^M \).

### 2.2 Airy Structures

In this section, we review some basic terminologies and facts about Airy Structures as introduced in [25].

#### 2.2.1 Topological vector spaces and symplectic structures

**Definition 2.2.1** A \( k \)-topological vector space \( V \) is a vector space equipped with a Hausdorff topology over a topological field \( k \) such that:

\[
\text{vector addition} : V \times V \to V, \quad \text{scalar multiplication} : k \times V \to V
\]  

(2.13)

are continuous.

We need a topology on \( V \) to define the dual space \( V^* := Hom(V, k) \) of \( V \) as the vector space of continuous linear functionals on \( V \). Typically, we equip \( V^* \) with the weakest topology such that the map \( f \in V^* \to \phi_v(f) := f(v) \in k \) is continuous for all \( v \in V \), making \( V^* \) also a topological vector space. Therefore, we have \( \phi_v \in V^{**} := Hom(V^*, k) \) by definition, where \( V^{**} \) is the vector space of continuous linear functionals on \( V^* \).

We will not assume vector spaces in this section to be finite-dimensional. To help with the notation when listing the basis or coordinates we introduce an index set \( I \). For example, we write the basis of \( V \) as \( \{e_{i \in I}\} \) and take \( I = \{1, ..., n\} \) if \( V \) is finite \( n \)-dimensional or \( \mathbb{I} = \mathbb{Z}_{>0} \) if \( V \) is countably infinite-dimensional.

**Remark 2.2.2** The topology of \( V \) will only be important to us when \( n \) is infinite because when \( n \) is finite, linear functionals on \( V \) are automatically continuous.

**Definition 2.2.3** A symplectic topological vector space \( (W, \Omega) \) is a pair consisting of a topological vector space \( W \) and a continuous antisymmetric bilinear form \( \Omega : W \times W \to k \) such that \( w \mapsto \Omega(w, \cdot) \) is an isomorphism \( W \cong W^* \). We call \( \Omega \) the *symplectic form* of \( W \).

Let us introduce the example of symplectic topological vector space \( (W, \Omega) \) which will be important in defining Airy structures. We will exclusively work with \( k := \mathbb{C} \) equipped with a discrete topology. Let \( V \) be a topological vector space with a discrete topology and a basis \( \{e_{i \in I}\} \) over \( \mathbb{C} \). Any vector \( v \in V \) can be written as \( v = \sum_{i \in I} y_i e^i \) where only a finite number of \( y_i \) in \( \mathbb{C} \) are non-zero. Let \( \{f_{i \in I}\} \subseteq V^* \) be the set of linearly independent vectors such that \( f_i(e^j) = \delta_{ij} \). Then elements of \( V^* \) are \( f = \sum_{i \in I} x_i f_i \) for \( x_i \in \mathbb{C} \). We call \( \{y_{i \in I}\} \) and \( \{x_{i \in I}\} \) coordinates of \( V \) and \( V^* \) respectively.Equip \( V^* \) with the weakest topology such that the map \( f \mapsto \phi_v(f) := f(v) \in \mathbb{C} \) is continuous for all \( v \in V \). The open sets in \( V^* \) take the form \( \bigcup_{j \in J} U_j \subseteq V^* \) where \( f \in V^* \) and \( J \subseteq I \) is a finite set and.

\[
U_j := \left\{ \sum_{i \in I \setminus J} x_i f_i \mid x_i \in \mathbb{C} \right\} \subseteq V^*.
\]  

(2.14)

**Remark 2.2.4** If \( V \) is finite dimensional then \( \{f_{i \in I}\} \) is a basis of \( V^* \). When the dimension is infinite, \( \{f_{i \in I}\} \) is a *Schauder basis* of \( V^* \) not an ordinary basis because their finite linear combination do not span \( V^* \). However, let us also refer to \( \{f_{i \in I}\} \) as a basis of \( V^* \) to simplify the language.

Finally, we define \( W := V \oplus V^* \) with standard symplectic form \( \Omega := \sum_{i \in I} dy_i \wedge dx^i \) where \( dy_i := f_i, \ dx^i := \phi_{e^i}, \)

\[
\Omega(e^i, e^j) = \Omega(f_i, f_j) = 0, \quad \Omega(e^i, f_j) = \delta^i_j.
\]  

(2.15)

\( \{e_{i \in I}, f_{i \in I}\} \) is a basis of \( W \). We call \( \{e_{i \in I}, f_{i \in I}\}, \) or any basis of \( W \) satisfying (2.15), a *canonical basis* of \( W \). To show that \( (W, \Omega) \) is a symplectic topological vector space we will need the following:

**Lemma 2.2.5** Let \( V \) be a discrete topological vector space with basis \( \{e_{k \in I}\} \) over a discrete topological field \( \mathbb{C} \), then \( V^{**} \cong V \).
2.2. Airy Structures

**Proof:** If \( V \) is finite-dimensional, this is trivial. Suppose that \( V \) is infinite-dimensional and let \( \phi \in V^{**} = Hom(V^*, \mathbb{C}) \) be a continuous linear functional. For any sequence \( s : \mathbb{Z}_{>0} \to V^*, n \mapsto s_n \) converges to \( f \in V^* \), we have \( \phi(f) = \phi(\lim_{n \to \infty} s_n) = \lim_{n \to \infty} \phi(s_n) \) by the continuity. Let us embed \( \mathbb{Z}_{>0} \) into the index set \( \mathbb{I} \). Suppose that \( f := \sum_{k \in \mathbb{Z}_{>0} \subseteq \mathbb{I}} x_k f_k \), where \( f(e^i) = \delta^i_1 \) and consider the sequence \( s_n := \sum_{k=1}^n x_k f_k + \Lambda_{n+1} f_{n+1} \) converges to \( f \) in the topology of \( V^* \) for any arbitrary sequence \( \{\Lambda_n\} \).

By the continuity of \( \phi \) we have
\[
\phi(f) = \phi(\lim_{n \to \infty} s_n) = \lim_{n \to \infty} \phi(s_n) = \lim_{n \to \infty} \phi \left( \sum_{k=1}^n x_k f_k + \Lambda_{n+1} f_{n+1} \right) = \lim_{n \to \infty} \left( \sum_{k=1}^n x_k \phi(f_k) + \Lambda_{n+1} \phi(f_{n+1}) \right).
\]

But the sequence \( \{\Lambda_n\} \) is arbitrary, therefore, the only way for the above to be true is if \( \phi(f_k) \) is only non-zero for finitely many \( n \in \mathbb{Z}_{>0} \subseteq \mathbb{I} \). Since the embedding of \( \mathbb{Z}_{>0} \) into \( \mathbb{I} \) is also arbitrary, we conclude that \( \phi(f_k) \) is non-zero for only finite number of \( k \in \mathbb{I} \).

The topology on \( V^{**} \) is given by the weakest topology such that the map \( \phi \mapsto \phi(f) \) is continuous for all \( f \in V^* \), which is not hard to check to be a discrete topology. The isomorphism \( V^{**} \cong V \) is given by \( e^i \leftrightarrow \phi_{e^i}, i \in \mathbb{I} \) where \( \phi_{e^i}(f_j) := f_j(e^i) = \delta^i_j \), proving the lemma.

Let us finish showing that \( (W, \Omega) \) is a symplectic topological vector space. We have that \( e^i \mapsto \Omega(e^i, \cdot) = \phi_{e^i} \) is an isomorphism \( V \xrightarrow{\cong} V^{**} \) and \( f_i \mapsto \Omega(f_i, \cdot) = -f_i \) is an isomorphism \( V^* \xrightarrow{\cong} V^* \). It follows that \( (W, \Omega) \) is a symplectic topological vector space because \( w \mapsto \Omega(w, \cdot) \) gives an isomorphism \( W = \mathbb{V} \oplus V^{**} \cong V^* \oplus V^* = (V^* \oplus V)^* = W^* \). The topological symplectic vector space \( W \) is an example of a Tate space.

**Definition 2.2.6 (Tate space [7])** A Tate space is a topological vector space over a discrete field \( k \) which is isomorphic to \( V_1 \oplus V_2^* \) for some discrete topological \( k \)-vector spaces \( V_1 \) and \( V_2 \).

**Remark 2.2.7** The coordinate \( x^i \) of \( V^* \) can be thought of as a linear functional \( x^i \in Hom(V^*, \mathbb{C}) = V^{**} \cong V \). Equivalently, \( x^i \) is identified with the vector \( e^i \in V \) via the isomorphism \( e^i \mapsto \Omega(e^i, \cdot) \). The reason why we are keeping both notations is that they carry different conceptual meanings. Similarly, the coordinate \( y_i \) can be identified with the vector \(-f_i \in V^*\). Together, \( \{x^i \in V_1, y_i \in V_2^*\} \) is a coordinate system of \( W \).

Given two vector spaces over a field \( k \), a tensor product is a frequently used operation to construct a new vector space. Formally, the tensor product \( V_1 \otimes V_2 \) of vector spaces \( V_1 \) and \( V_2 \) is uniquely defined up to isomorphism as the vector space satisfying a certain universal property. More concretely, suppose that \( V_1 \) and \( V_2 \) are potentially infinite-dimensional vector spaces with bases \( \{e_1^i \}_{i \in \mathbb{I}_1} \) and \( \{e_2^i \}_{i \in \mathbb{I}_2} \) respectively, then \( V_1 \otimes V_2 \) is a vector space with a basis \( \{e_1^i \otimes e_2^j \mid (i, j) \in \mathbb{I}_1 \times \mathbb{I}_2\} \). In other words,
\[
V_1 \otimes V_2 = \left\{ \sum_{(i,j) \in \mathbb{I}_1 \times \mathbb{I}_2} v_{ij} e_1^i \otimes e_2^j \mid v_{ij} \in k \text{ is non-zero for finitely many pairs of } (i, j) \in \mathbb{I}_1 \times \mathbb{I}_2 \right\}. \tag{2.16}
\]

**Remark 2.2.8** The important message of (2.16) is that only finite linear combinations of tensor products of vectors are allowed in \( V_1 \otimes V_2 \) even though \( V_1 \) or \( V_2 \) are possibly infinite-dimensional.

\( V_1 \otimes V_2 \) is different from the **topological complete tensor product** \( V_1 \hat{\otimes} V_2 \) mentioned in [25]. Let us briefly explain the meaning of \( V_1 \hat{\otimes} V_2 \). Given a topological vector space \( V \), the completion of \( V \) is the unique complete topological vector space \( \hat{V} \) such that \( V \) can be embedded densely into \( \hat{V} \) [37, Theorem 5.2]. Let \( V_1, V_2 \) be topological vector spaces. We assign the topology to \( V_1 \otimes V_2 \) such that it is the unique object satisfying the universal properties of the tensor product in the category of \( k \)-topological vector spaces [18]. For instance, when \( V_1 \) and \( V_2 \) are locally convex, then this topology on \( V_1 \otimes V_2 \) is the projective topology [37, Definition 43.2].

**Definition 2.2.9** The **topological complete tensor product** \( V_1 \hat{\otimes} V_2 \) is the topological completion of the tensor product \( V_1 \otimes V_2 \).

Let us give an explicit presentation of \( W \hat{\otimes} W \) as an example, where \( W = V \oplus V^* \) is a Tate space. Assign a topology to \( W \otimes W \) by declaring open sets around \( w \in W \) to be \( w + U_{1,2,3,5} \subseteq W \otimes W \) where \( J_{k=1,2} := \{3\} \), \( J_1, J_2, J_3 \subseteq \mathbb{I} \) are finite sets and
\[
U_{1,2,3,5} := \sum_{i \in \mathbb{I}} \left( U_1^i \otimes C e^i + C e^i \otimes U_2^i \right) + \sum_{J_3 \subseteq 1, J_2 \subseteq 1} U_1 \otimes U_2 \subseteq W \otimes W.
\]
where $U_j \subseteq V^*$ are vector subspaces given by \([2.14]\). Since open neighborhoods of zero $U_{j_1,j_2,j_3}$ are subspaces of $W \otimes W$ in this case, the completion can be computed using the inverse limit:

$$W \hat{\otimes} W := \lim_{\longleftarrow} W \otimes W / U_{j_1,j_2,j_3}$$

$$= \left\{ \sum_{i,j \in I} a_{ij} e^i \otimes e^j + \sum_{i,j \in I} (b_{ij} e^i \otimes f_j + b_{ji} f_i \otimes e^j) \right\} \cap \left\{ a_{ij}, b_{ij}, c_{ij} \in \mathbb{C} \right\}$$

$$\text{for finitely many pairs of } (i,j) \in I \times I,$n \in \mathbb{N}$$

$$\text{for finitely many } j \in I \right\}.$$

For $k = 1, 2$, let us write $J''_k \subseteq J'_k$ if $J''_k \subseteq J'_k$ for all $i \in I$. The inverse limit is taken over the directed set of tuples $(J_1, J_2, J_3)$ with partial order $(J'_{i_1}, J'_{i_2}, J'_{i_3}) \leq (J_1, J_2, J_3)$ if $J''_{i_1} \subseteq J_{i_1}, \forall i = 1, 2, 3.$

The $n$-th order topological complete tensor product $W^{\hat{\otimes}n} := W \hat{\otimes} \cdots \hat{\otimes} W$ can be defined in a similar way. We denote by $\hat{\text{Sym}}_n(W)$ the subspace of symmetric tensors in $W^{\hat{\otimes}n}$ and let $\hat{\text{Sym}}_{\leq n}(W) := \bigoplus_{i=0}^n \hat{\text{Sym}}_i(W).$ Using Remark 2.2.7, we can think of $\prod_{i=0}^\infty \hat{\text{Sym}}_i(W)$ as the space of formal polynomials on $W$ and denote it by $\mathbb{C}[W] = \mathbb{C}[x^{i_1}, y_{j_1}]$. In particular, elements of $\mathbb{C}[W]$ are formal series of the form

$$\sum_{n=0}^\infty \sum_{i_1^{n_2}, n_1 \geq 0} \sum_{j_1^{n_2}, n_1 \geq 0} P_{i_1, \ldots, i_n} x^{i_1} \cdots x^{i_n} y_{j_1} \cdots y_{j_n},$$

Where $P_{i_1, \ldots, i_n} \in \mathbb{C}$ and

- for each $(j_1, \ldots, j_n) \in \mathbb{N}^n, P_{i_1, \ldots, i_n} \neq 0$
- for finitely many $(i_1, \ldots, i_n) \in \mathbb{N}^n.$

The symplectic form $\Omega$ defines a Poisson bracket on $\mathbb{C}[W]$ given by

$$\{ x^i, x^j \} = \{ y_i, y_j \} = 0,$n \neq j \}$

and extended to arbitrary formal polynomials by the Leibniz rule. We call coordinates $\{ x^{i_1}, y_{j_1} \}$ satisfying \[2.17\], or equivalently coordinates such that $\Omega$ takes canonical form: $\Omega = \sum_{i \in \mathbb{N}} d y_i \wedge d x^i$, a canonical coordinates system of $W$.

### 2.2.2 Pre-Airy structures

Let $V$ be a topological vector space with a discrete topology over the discrete topological field $\mathbb{C}$.

**Definition 2.2.10** ([25, Definition 2.6.1]) A classical pre-Airy structure on $V$ is a tuple $(V, A, B, C)$ where

\[ A = (a_{ijk})_{i,j,k \in I} \in V \otimes V \otimes V, \quad B = (b_{ij}^k)_{i,j,k \in I} : V \to V \otimes V, \quad C = (c_{ijk}^l)_{i,j,k,l \in I} : V \otimes V \to V. \]

A quantum pre-Airy structure on $V$ is a tuple $(V, A, B, C, \epsilon)$ where $(V, A, B, C)$ is a classical pre-Airy structure and $\epsilon = (\epsilon_i) \in V$.

**Remark 2.2.11** Equivalently, (a quantum) pre-Airy structure is given by any $A = (a_{ijk})_{i,j,k \in I}, B = (b_{ij}^k)_{i,j,k \in I}, C = (c_{ijk}^l)_{i,j,k,l \in I}$ and $\epsilon = (\epsilon_i)$ such that: $a_{ijk}, \epsilon_i \in \mathbb{C}$ are non-zero for only finitely many $(i,j,k) \in I \times I \times I$ and $b_{ij}^k \in \mathbb{C}$ is non-zero for only finitely many $(i,j) \in I \times I$ for each $k \in I$ and $c_{ijk}^l \in \mathbb{C}$ is non-zero for only finitely many $i \in I$ for each $(j,k) \in I \times I$.

Given a quantum pre-Airy structure $(V, A, B, C, \epsilon)$ there exists a recursive procedure called Abstract Topological Recursion (ATR) \[25\] Section 2.5 produces a set of numbers $\{ S_{g,n,i_1, \ldots, i_n} \in \mathbb{C} \mid i_k \in I \}$. Let the basis of $V$ be $\{ e^{i_1} \}$.

We package the set of numbers $\{ S_{g,n,i_1, \ldots, i_n} \}$ into the tensor

\[ S_{g,n} := \sum_{i_1, \ldots, i_n} \frac{1}{n!} S_{g,n,i_1, \ldots, i_n} e^{i_1} \otimes \cdots \otimes e^{i_n} \in V^{\otimes n} = V \otimes \cdots \otimes V. \]

As the name suggests, ATR is related to topological recursion. We will see later this chapter the quantum pre-Airy structure such that the ATR reduces to the usual topological recursion.

Let us now describe ATR in details. We set the initial conditions to be

\[ S_{0,3} := 2 A \in V \otimes V \otimes V, \quad S_{1,1} := \epsilon \in V, \quad S_{0, \leq 2} = S_{g \geq 0,0} = 0. \]
Then \( S_{g,n} \) for \( g \geq 0, n \geq 4 \) or \( g \geq 2, n \geq 1 \) or \( g \geq 1, n \geq 2 \) are computed recursively as follows

\[
S_{g,n;i_1,...,i_n} = 2 \sum_{k=2}^{n} \sum_{j \in 1} b_{i_1}^{j} S_{g,n-1;j_{i_1}(2,...,n)\setminus(k)} + \sum_{g_1+g_2=g} \sum_{j_1,j_2 \in 1} C_{i_1}^{j_1j_2} S_{g_1,1+j_{i_1}j_{i_2}+1;j_{i_2}+2} + \sum_{j_1,j_2 \in 1} C_{i_1}^{j_1j_2} S_{g-1,n+1;j_{i_1}j_{i_2}...i_n}.
\]

Note that the right-hand-side of (2.18) only involve \( S_{g',n'} \) with \( 2g' - 2 + n' < 2g - 2 + n \), therefore the recursion is guaranteed to terminate.

**Remark 2.2.12** The right-hand-side of (2.18) will indeed define an element of \( V^\otimes n \). Let \( v := \sum_{k \in 1} v_k e^k \in V, u := \sum_{k \in 1} u_k e^k \in V \), then by definition we have \( \sum_{i,j,k \in 1} C_{i}^{j} v_k u_k e^j = C(v \otimes u) \in V \). Note that all summations came from contractions of a vectors in \( V \) and \( V^* \), so they have at least finitely many terms even though the cardinality of the index set \( I \) may be infinite.

Given \( g, n \) and suppose that \( S_{g',n'} \in V^\otimes n' \) for all \( 2g' - 2 + n' < 2g - 2 + n \) then it follows that the first and second terms in (2.18) are well-defined elements of \( V^\otimes n \). Finally, the last term of (2.18) is a well-defined element of \( V^\otimes n \) because \( S_{g-1,n+1} \in V^\otimes n+1 \), a non-completed tensor products of \( V \), so it contains only finite linear combination of tensor products of vectors in \( V \). More explicitly, we can write \( \sum_{j_1,j_2 \in 1} S_{g-1,n+1;j_{i_1}j_{i_2}...i_n} e^{j_1} \otimes e^{j_2} \) as a finite sum \( \sum_{k=1}^{N} v_{1,k} \otimes v_{2,k} \) for some \( v_{1,k}, v_{2,k} \in V \) and \( N \in \mathbb{Z}_{\geq 0} \). Then

\[
\sum_{j_1 \in 1} \sum_{j_2 \in 1} C_{i_1}^{j_1j_2} S_{g-1,n+1;j_{i_1}j_{i_2}...i_n} e^{j_1} \otimes e^{j_2} = C \left( \sum_{j_1,j_2 \in 1} S_{g-1,n+1;j_{i_1}j_{i_2}...i_n} e^{j_1} \otimes e^{j_2} \right) = C \left( \sum_{k=1}^{N} v_{1,k} \otimes v_{2,k} \right) = \sum_{k=1}^{N} C(v_{1,k} \otimes v_{2,k}) \in V.
\]

Overall, the output \( S_{g,n} \) is a well-defined element of \( V^\otimes n \).

**Definition 2.2.13** (25 Definition 2.6.1) A classical pre-Airy sub-structure \((U, A, B, C)\) of \((V, A, B, C)\) is a classical pre-Airy structure given by a vector subspace \( U \subseteq V \) compatible with tensors \( A, B, C \) in the sense that

\[
A \in U \otimes U \otimes U, \quad B|_U : U \rightarrow U \otimes U, \quad C|_{U \otimes U} : U \otimes U \rightarrow U.
\]

A quantum pre-Airy sub-structure \((U, A, B, C, \epsilon)\) of \((V, A, B, C, \epsilon)\) is a quantum pre-Airy structure given by a classical pre-Airy sub-structure \((U, A, B, C)\) of \((V, A, B, C)\) such that \( \epsilon \in U \).

A (quantum or classical) pre-Airy structure on \( V \) is called primitive if it does not contain a non-trivial (quantum or classical) pre-Airy sub-structure \((U, A, B, C, \epsilon)\) with \( U \lneq V \).

**Remark 2.2.14** Given two quantum pre-Airy structures \((V_i, A_i, B_i, C_i, \epsilon_i)\) and their ATR outputs \( \{ S^{(i)}_{g,n} \in V_i^\otimes n \}, i = 1, 2 \) the important feature is the following. If both quantum pre-Airy structures \((V_i, A_i, B_i, C_i, \epsilon_i), i = 1, 2 \) contain the same quantum pre-Airy sub-structure \((V, A, B, C, \epsilon)\), i.e. \( V \subseteq V_1, V_2 \) and

\[
A_1 = A = A_2, \quad B_1|_V = B = B_2|_V, \quad C_1|_{V \otimes V} = C = C_2|_{V \otimes V}, \quad \epsilon_1 = \epsilon = \epsilon_2
\]

then their ATR outputs will be the same 25 Section 2.6; \( S^{(1)}_{g,n} = S^{(2)}_{g,n} = S_{g,n} \in V^\otimes n \subseteq V_1^\otimes n, \quad i = 1, 2 \) where \( \{ S_{g,n} \in V^\otimes n \} \) is the output of ATR using the pre-Airy structure \((V, A, B, C, \epsilon)\).

### 2.2.3 Airy structures

In this section we let \( W = V \otimes V^* \) be a Tate space and let \( \{ x^i e^j, y^i e^j \} \) be canonical coordinates of \( W \).

**Definition 2.2.15** (25 Definition 2.1.1) A classical Airy structure on \( V \) is a classical pre-Airy structure \((V, A, B, C)\) such that the collection of at-most quadratic polynomials \( \{ H_{i} \in Sym_{\leq 2}(W) \} \), where

\[
H_i := -y_i + \sum_{j,k \in 1} a_{ijk} x^j x^k + 2 \sum_{j,k \in 1} b_{ij}^k x^j y_k + \sum_{j,k \in 1} c_{ij}^k y_j y_k,
\]

(2.19)
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generates the vector space \( \mathfrak{g} := \bigoplus_{i \in \mathbb{C}} \mathcal{H}_i \subset \mathcal{S}ym_{\leq 2}(W) \) which is closed under the Poisson bracket: \( \{ \mathcal{H}_i, \mathcal{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \mathcal{H}_k \in \mathfrak{g} \) for some structure constants \( g_{ij}^k \in \mathbb{C} \). In other words, the structure constants \( g_{ij}^k \) are the matrix entries of the operator \( \mathfrak{g} \) is a Lie algebra with Lie bracket given by the Poisson bracket.

Remark 2.2.16 We can always assume that the tensors \( A = (a_{ij}) \) and \( (c_i^k) \) are symmetric in the indices \( i, j \) because their anti-symmetric part would vanish in the expression of \( \mathcal{H}_i \). Given \( \mathcal{H}_i \) by summing against \( x^i x^k \) and \( y_j y_k \). On the other hand, the tensor \( B = (b_{ij}) \) does not possess any symmetry in the indices \( i, j \).

In fact, given a classical Airy structure \( \{ \mathcal{H}_i, \mathcal{H}_j \} \in \mathcal{S}ym_{\leq 2}(W) \), it can be shown (see [1] Section 2.2.1, [25] Section 2.1) from \( \{ \mathcal{H}_i, \mathcal{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \mathcal{H}_k \) that \( a_{ij} \) is symmetric in the indices \( i, j \) and that \( g_{ij}^k = 2(b_{ij}^k - b_{ji}^k) \). In other words, \( a_{ij} \) is symmetric in all indices \( i, j, k \) and the structure constants \( g_{ij}^k \) are components of the tensor \( (g_{ij}^k)_{i, j, k \in \mathbb{C}} : V \rightarrow V \otimes V \) which is entirely determined by the tensor \( B \).

Remark 2.2.17 Note that each \( \mathcal{H}_i \) may be treated as a function \( \mathcal{H}_i : W \rightarrow \mathbb{C} \). Denote by \( \mathcal{H}_i(w) \) the evaluation of \( \mathcal{H}_i \) at a point \( w := \sum_{i \in \mathbb{C}} (x^i f_i + y_i e_i) \in W \) where \( x^i, y_i \in \mathbb{C} \), then \( H := \sum_{i \in \mathbb{C}} H_i(w) e_i \in V \).

Let us define the Weyl algebra \( D^h(W) := \mathcal{C}[x^i, h \partial x^i][h] \) where \( h \partial := h \frac{\partial}{\partial x^i} \). We introduce grading on \( D^h(W) \) by setting \( h = 2, \deg x^i = 1, \deg h = 1 \). Let \( D^h_0 \) be the vector subspace of degree \( n \) elements in \( D^h(W) \) and let \( D^h_{\leq n}(W) := \bigoplus_{n = 0}^\infty D^h_n(W) \). We also introduce the following notations when working with \( D^h(W) \):

Definition 2.2.18 Let \( \hat{f}, \hat{g} \in D^h(W) \). We denote applying the operator \( \hat{f} \) on \( \hat{g} \) by \( \hat{f} \hat{g} \). We denote multiplying the operator \( \hat{f} \) with the operator \( \hat{g} \) by \( \hat{f} \hat{g} \). For example, \( h \partial h \partial = h \partial + h \partial = h^2 \partial + x^i h \partial_x \).

Conceptually, \( D^h(W) \) is the quantization of \( \mathbb{C}[W] \) with \( y_i \) replaced by \( h \partial y_i \) and the Poisson bracket \( \{ \ldots \} \) replaced by the commutator \( \frac{1}{h}[\ldots, \ldots] \) with \( [\hat{f}, \hat{g}] := \hat{f} \hat{g} - \hat{g} \hat{f} \in \mathcal{D}^h(W) \). We define the classical limit to be the map \( \text{cl} : \mathcal{D}^h(W) \rightarrow \mathbb{C}[W] \), given by \( h \hat{\rightarrow} 0, x^i \hat{\rightarrow} x^i \), and \( \hat{h} \hat{\rightarrow} y_i \).

Definition 2.2.19 ([25, Definition 2.2.1]) A quantum Airy structure on \( V \) is a collection \( \{ \hat{H}_i \in \mathcal{D}^h_{\leq 2}(W) \} \) such that \( \hat{g} := \bigoplus_{i \in \mathbb{C}} \hat{H}_i \subset \mathcal{D}^h_{\leq 2}(W) \) is a Lie algebra with Lie bracket given by the commutator \( \frac{1}{h}[\ldots, \ldots] \). In other words, \( \frac{1}{h} \{ \hat{H}_i, \hat{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \hat{H}_k \in \hat{g} \) for some constants \( g_{ij}^k \in \mathbb{C} \).

A classical Airy structure \( \{ \mathcal{H}_i \} \) is called the classical limit of \( \{ \hat{H}_i \} \) if \( \mathcal{H}_i = \text{cl}(\hat{H}_i) \) in which case we also have \( \{ \mathcal{H}_i, \mathcal{H}_j \} = \text{cl} \left( \frac{1}{h} \{ \hat{H}_i, \hat{H}_j \} \right) = \sum_{k \in \mathbb{C}} g_{ij}^k \mathcal{H}_k \). We say that \( \{ \hat{H}_i \} \) quantizes or it is a quantization of \( \{ \mathcal{H}_i \} \).

Remark 2.2.20 The condition \( \frac{1}{h} \{ \hat{H}_i, \hat{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \hat{H}_k \) can be written as relations among tensors \( A, B, C \) and \( \epsilon, [\cdot, \cdot] \). If we ignored all relations involving \( \epsilon \), then the remaining are relations among \( A, B \) and \( C \) arise from the classical condition \( \{ \mathcal{H}_i, \mathcal{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \mathcal{H}_k \).

Remark 2.2.21 Quantization is more difficult than just replacing \( x^i \) by \( x^i \) and \( y_i \) by \( h \partial y_i \) because \( \mathbb{C}[W] \) is a commutative algebra whereas \( \mathcal{D}^h(W) \) is non-commutative, hence there is an ambiguity in ordering \( x^i \) and \( h \partial y_i \). For instance, it is unclear whether the term \( x^i y_j \) should be quantized as \( x^i h \partial y_j \) or \( h \partial x^i y_j = h \partial x^i y_j + x^i h \partial y_j \).

In general, suppose that \( \hat{f}, \hat{g}, \hat{h} \in \mathcal{D}^h_{\leq 2}(W) \) with classical limit \( f = \text{cl}(\hat{f}), g = \text{cl}(\hat{g}), h = \text{cl}(\hat{h}) \in \mathcal{S}ym_{\leq 2}(W) \) then \( \{ \hat{f}, \hat{g} \} = h \) implies \( \{ f, g \} = h \) but on the other hand, if \( \{ f, g \} = h \) then \( \{ \hat{f}, \hat{g} \} = \{ f, g \} + c = h + c \) for some constant \( c \in \mathbb{C} \). Therefore, the quantization of \( \{ \mathcal{H}_i \} \) where \( \mathcal{H}_i \) are given by (2.19) and \( [\mathcal{H}_i, \mathcal{H}_j] = \sum_{k \in \mathbb{C}} g_{ij}^k \mathcal{H}_k \) amount to finding \( \{ \epsilon_{i,j} \} \subset \mathbb{C} \) such that

\[
\hat{H}_i := -h \partial_i + \sum_{j, k \in \mathbb{C}} a_{ijk} x^i x^k + 2h \sum_{j, k \in \mathbb{C}} b_{ijk} x^i \partial_k + h^2 \sum_{j, k \in \mathbb{C}} c_{ijk} x^i \partial_j \partial_k + h \epsilon_i
\]

(2.20)

satisfying \( \frac{1}{h} \{ \hat{H}_i, \hat{H}_j \} = \sum_{k \in \mathbb{C}} g_{ij}^k \hat{H}_k \).

If follows from (2.20) we can write a quantum Airy structure on \( V \) as a tuple \( (V, A, B, C, \epsilon) \). In other words, a quantum Airy structure is a quantum pre-Airy structure \( (V, A, B, C, \epsilon) \) such that \( \hat{g} := \bigoplus_{i \in \mathbb{C}} \mathcal{H}_i \), where \( \mathcal{H}_i \) given by (2.20), is a Lie algebra.

Given a classical Airy structure \( \{ \mathcal{H}_i \} \), then neither the uniqueness nor existence of its quantization is guaranteed in general. It turns out that the sufficient condition for the existence of quantization of \( \{ \mathcal{H}_i \} \) is given by the vanishing of the second cohomology of Lie algebra \( H^2(\mathfrak{g}, \mathbb{C}) \). On the other hand, the necessary and sufficient condition for the uniqueness of the quantization is given by the vanishing of \( H^1(\mathfrak{g}, \mathbb{C}) \) [25].
2.2. Airy Structures

We will often refer to classical (pre-)Airy structures simply as (pre-)Airy structures unless it is important to emphasize their distinction from quantum (pre-)Airy structures.

There is a correspondence between Airy structures and quadratic Lagrangian submanifolds $L := \{ H_{i_1} = 0 \}$ of $W$, i.e. Lagrangian submanifolds defined by at-most quadratic polynomials in $W$. When $V$ is finite-dimensional, this correspondence is easy:

**Lemma 2.2.22 ([25, Section 2.1])** Let $V$ be an $n$-dimensional vector space and $\{ H_1, \ldots, H_n \}$ is a collection of at-most quadratic polynomials on $W = V \oplus V^*$ in the form given in (2.17). Then $L := \{ H_i = 0 \} \subset W$ is a Lagrangian submanifold if and only if the collection $\{ H_1, \ldots, H_n \}$ gives an Airy structure.

**Proof:** Suppose that $\{ H_1, \ldots, H_n \}$ is an Airy structure. Let $v_{H_i}$ be a Hamiltonian vector field corresponding to $H_i$, i.e. $\iota_{v_{H_i}} \Omega = dH_i$. Then $v_{H_i} \in T_L$ for all $x \in L$ because $v_{H_i}(x) = H_i(x) = 0$. Because $\dim L = n$, we conclude that $\{ v_{H_1}(x), \ldots, v_{H_n}(x) \}$ is a basis of $T_x L$. Finally, $\Omega(v_{H_i}, v_{H_j}) = \{ H_i, H_j \} = 0$ on $L$ and $\dim L = \frac{1}{2} \dim W$, therefore $L \subset W$ is a Lagrangian submanifold.

Conversely, suppose that $L \subset W$ is a Lagrangian submanifold. Then for all $v \in T_v L$ we have $\Omega(v_{H_i}(x), v) = \iota_v dH_i(x) = 0$. Because $T_v L \subset W$ is a Lagrangian subspace, i.e. a maximal isotropic subspace, it follows that $v_{H_i} \in T_v L$. Then $\{ H_i, H_j \}(x) = \Omega(v_{H_i}, v_{H_j}) = 0$ for all $x \in L$, which means $\{ H_i, H_j \}$ belongs to an ideal generated by $\{ H_1, \ldots, H_n \}$. But each $H_i$ is at most quadratic, so $\{ H_i, H_j \}$ also is at most quadratic, we conclude that $\{ H_i, H_j \} = \sum_i g^k_{ij} H_k$ for some constants $g^k_{ij} \in \mathbb{C}$.

**Remark 2.2.23** When $V$ is finite dimensional, we define the tangent space to $L$ at $x \in L \subset W$ to be

$$T_x L := \{ v \in W \mid \iota_v dH_i(x) = 0, i = 1, \ldots, n \}.$$ 

It is more subtle how to interpret this definition when $V$ is infinite-dimensional, except at $x = 0 \in W$. It is easy to see from the form of each $H_i$ in (2.19) even when $V$ is infinite-dimensional that $H_i(0) = 0$ and $dH_i(0) = dy_i$ for all $i \in I$, therefore we define $\mathcal{T}_L := \{ y_{i \in I} = 0 \} = V^* \subset W$ which is a Lagrangian subspace of $W$. Since $V \subset W$ is also a Lagrangian subspace of $W$ and $W = V \oplus V^* \cong V \oplus \mathcal{T}_L$ we call $V$ a Lagrangian complement of $\mathcal{T}_L$.

When $V$ is infinite-dimensional the arguments used in the proof of Lemma 2.2.22 will no longer hold. Instead, what we mean by quadratic Lagrangian submanifold is that there exists a generating function $S_0 \in \prod_{n=1}^{\infty} Sym_n(V)$ such that

$$H_i \left( \{ x^{i_1} \}, \left\{ y_{i_1} \equiv \frac{\partial S_0}{\partial x^{i_1}} \right\} \right) = 0, \quad i \in I.$$  

(2.21)

We are going to show this in a moment. Keep in mind that $\partial_i S_0 = \frac{\partial S_0}{\partial x^{i_1}} \in \prod_{n=1}^{\infty} Sym_n(V)$ is a formal derivative and should be understood as: the image of $H_i$ under the homomorphism $\hat{Sym}_{\leq 2}(W) \to \prod_{n=1}^{\infty} Sym_n(V), x^i \mapsto x^i, y_{i_1} \mapsto \partial_i S_0$ is zero.

Note that we can think of a quantum Airy structures $\{ \hat{H}_{i_1} \}$ as a quantization of a quadratic Lagrangian submanifold $L := \{ H_{i_1} = 0 \}$. Let us consider solving for $\psi_L$ such that $\psi_L^{-1} \hat{H}_i(\psi_L) = 0$ where $\psi_L$ is given by the formal expression

$$\psi_L := \exp \left( \sum_{g=0}^{\infty} \hbar^{g-1} S_g \right), \quad S_g = \sum_{n=0}^{\infty} \sum_{n=1}^{\infty} S_{g,n} \in \prod_{n=1}^{\infty} Sym_n(V),$$  

(2.22)

such that $\psi_L^{-1}(h \partial_i) \psi_L := h \partial_i + \partial_i \left( \sum_{g=0}^{\infty} \hbar^g S_g \right)$ and each $S_{g,n}$ are homogeneous polynomial of degree $n$:

$$S_{g,n} := \sum_{i_1, \ldots, i_n} \frac{1}{i_1!} S_{g,n,i_1,\ldots,i_n} x^{i_1} \cdots x^{i_n} \in Sym_n(V).$$  

(2.23)

Observe that $S_{g,n} \in Sym_n(V)$ without completion of symmetric tensor product and $S_g$ is a formal sum of $S_{g,n}$. The following Proposition guarantee the existence and uniqueness of the solution $\psi_L$:

**Theorem 2.2.24 ([25, Theorem 2.4.2])** Let $\{ \hat{H}_{i_1} \}$ be a quantum Airy structure. There exists a unique solution of the form $\psi_L$ of the form (2.22) such that $\psi_L^{-1} \hat{H}_i(\psi_L) = 0, \forall i \in I$. 

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Proof: First of all, we note that if $\psi := \exp \left( \sum_{g=0}^{\infty} h^{g-1} \sum_{n=0}^{\infty} S_{g,n} \right)$ for an arbitrary $S_{g,n} \in \text{Sym}_n(V)$ then $\psi^{-1} \tilde{H}_i \psi \in \mathcal{D}^h(W)$. To verify this we need to check that for each $g$ and $n$, the degree $n$ term of the coefficient of $h^n$ in $\psi^{-1} \tilde{H}_i \psi(1)$ belongs to $\text{Sym}_n(V)$. These type of terms came from

$$H_i^{(g,n)} := -h^2 \partial_i S_{g,n+1} + h^g \sum_{j,k \in \mathbb{E}} b_{ij}^k x^j \partial_k S_{g,n} + h^g \sum_{n_1, n_2, n_3} c_{ij}^{k} \partial_j S_{g_1,n_1} \partial_k S_{g_2,n_2} + h^g \sum_{j,k \in \mathbb{E}} c_{ij}^k \partial_j \partial_k S_{g-1,n+2}.$$  \hfill (2.24)

The first term belongs to $\text{Sym}_n(V)h^g$. Since $\sum_{k \in \mathbb{E}} b_{ik} \partial_k S_{g,n}$ is the same as contracting the tensor $B$ with $S_{g,n}$, by Remark 2.2.12 the second term also belongs to $\text{Sym}_n(V)h^g$. Similarly, by Remark 2.2.12 we also conclude that the third and the fourth terms also belong to $\text{Sym}_n(V)h^g$. This verifies our claim that $\psi^{-1} \tilde{H}_i \psi \in \mathcal{D}^h(W)$.

The proof is by induction in $g$ and for each fixed $g$ we proceed with induction in $n$. Suppose that we have found the solution $S_{g}$ for all $g = 0, \ldots, g_0 - 1$ and for $S_{g_1}$ up to degree $n_0$ term in the sense that if $\psi_L^{(g,n)} := \exp \left( \sum_{g=0}^{g_0-1} h^{g-1} S_g + h^{n_0-1} \sum_{g=0}^{n_0} S_{0,g} \right)$ then

$$\tilde{H}_i^{(g,n)} := (\psi_L^{(g,n)-1})^{-1} \tilde{H}_i \psi_L^{(g,n)}$$

$$= -h \partial_i + H_i^{(g,n)} + h^{n_0+1} x^{g_1} + h^{g_1+n_0+1} + 2h \sum_{j,k \in \mathbb{E}} b_{ij}^k x^j \partial_k + h^2 \sum_{j,k \in \mathbb{E}} c_{ij}^k \partial_j \partial_k \in \mathcal{D}^h(W),$$  \hfill (2.25)

where $H_i^{(g,n)} := h^{n_0+x^{g_1}} \in \text{Sym}_n(V)h^{n_0}$. Since $\{\tilde{H}_i\}$ is a quantum Airy structure we can check that $\{\tilde{H}_i^{(g,n)}\}$ satisfies the similar commutation relations

$$\frac{1}{h} [\tilde{H}_i^{(g,n)}, \tilde{H}_j^{(g,n)}] = \frac{1}{h} \left( \tilde{H}_j^{(g,n)} \tilde{H}_i^{(g,n)} - \tilde{H}_i^{(g,n)} \tilde{H}_j^{(g,n)} \right) = \frac{1}{h} (\psi_L^{(g,n)})^{-1} \left( \tilde{H}_i \tilde{H}_j - \tilde{H}_j \tilde{H}_i \right) \psi_L^{(g,n)}$$

$$= (\psi_L^{(g,n)})^{-1} \left( \frac{1}{h} [\tilde{H}_i, \tilde{H}_j] \right) \psi_L^{(g,n)} = \sum_{k \in \mathbb{E}} g_{ij}^k \tilde{H}_k^{(g,n)}.$$  \hfill (2.26)

The left hand side of (2.26) contains the term $\partial_j \left( \tilde{H}_i^{(g,n)} \right) - \partial_i \left( \tilde{H}_j^{(g,n)} \right) = h^{n_0+x^{g_1}-1}$ but the right hand side only contain $h^{g_1+n_0-x^{g_1}}$, so it must be the case that $\partial_i \left( \tilde{H}_j^{(g,n)} \right) = \partial_i \left( \tilde{H}_j^{(g,n)} \right)$. In other words, there exists a symmetric tensor $S_{g_0,n_0+1} := \sum_{i_1, \ldots, i_{n_0+1}} S_{g_0,n_0+1, i_1, \ldots, i_{n_0+1}} x^{i_1} \cdots x^{i_{n_0+1}} \in \text{Sym}_{n+1}(V)$ such that $H_i^{(g_0,n_0)} = h^{n_0} \partial_i S_{g_0,n_0+1}$.

For the base case of the induction, $(g_0, n_0) = (0, 0)$, we look at the first non-trivial $S_{0,n_0}$ which is $S_{0,0} = 2A \in \text{Sym}_0(V)$. By setting $\psi_L^{(0,3)} := \exp \left( \frac{1}{h} S_{0,3} \right)$ we can see that $\psi_L^{(0,3)} = \psi_L^{(0,3)}$ takes the form of (2.25) with $(g_0, n_0) = (0, 3)$.

Taking the limit $h \to 0$ of the expression $\psi_L^{-1} \tilde{H}_i \psi_L(1) = 0$ is the same as replacing every $\partial_i$ in $\tilde{H}_i$ with $\partial_i S_0$. Therefore, we obtain (2.21), showing that $S_0 = \sum_{n=0}^{\infty} \sum_{g=0}^{\infty} S_{g,n} \in \mathcal{I}_{\text{Sym}_n}(V)$ is the generating function of $L = \{H_i = 0\}$. It is in this sense that $\psi_L$ is considered a quantization of $L$. The following Corollary of Theorem 2.2.24 makes the relationship between quantum Airy structures and ATR becomes clear:

Corollary 2.2.25 If a quantum pre-Airy structure $(V, A, B, C, \epsilon)$ is a quantum Airy structure then the output $S_{g,n} \in V^{\otimes n}$ of the corresponding ATR are symmetric tensors. Moreover, if $\psi_L := \exp \left( \sum_{g=0}^{\infty} h^{g-1} \sum_{n=0}^{\infty} S_{g,n} \right)$ then $\psi_L^{-1} \tilde{H}_i(\psi_L) = 0$.

Proof: Theorem 2.2.24 tells us that the solution to $\psi_L^{-1} \tilde{H}_i(\psi_L) = 0$ of the form $\psi_L := \exp \left( \sum_{g=0}^{\infty} h^{g-1} \sum_{n=0}^{\infty} S_{g,n} \right)$ where $S_{g,n} \in \text{Sym}_n(V)$ exists. The equation $\psi_L^{-1} \tilde{H}_i(\psi_L)(1) = 0$ implies that the right-hand side of (2.24) must vanish. In particular, the coefficient of each $x^{i_1} \cdots x^{i_{n+1}}, i_k \in \mathbb{E}$ must vanish and this gives us the recursion relations (2.18). \hfill \Box

Finally, the notion of sub-structures we introduced for (quantum) pre-Airy structures translates straightforwardly to the notion of sub-structures for (quantum) Airy structures:

Definition 2.2.26 (Section 2.6) A classical Airy sub-structure $(U, A, B, C, \epsilon)$ of a classical Airy structure $(V, A, B, C)$ is a classical pre-Airy sub-structure of a pre-Airy structure $(V, A, B, C)$. A quantum Airy sub-structure $(U, A, B, C, \epsilon)$ of a quantum Airy structure $(V, A, B, C, \epsilon)$ is a quantum pre-Airy sub-structure of a quantum pre-Airy structure $(V, A, B, C, \epsilon)$. 27
Lemma 2.2.27 (25, Section 2.6) An Airy sub-structure of an Airy structure is an Airy structure. A quantum Airy sub-structure of a quantum Airy structure is a quantum Airy structure.

Proof: According to Remark 2.2.29 certain relations among A, B, C and ε are satisfied if and only if A, B, C and ε define a (quantum) Airy structure. The fact that we can restrict these tensors to a subspace $U \subset V$ will not affect these relations.

2.2.4 Gauge transformation of (quantum) Airy structures

Given an Airy structure $(V, A, B, C)$, it defines a quadratic Lagrangian submanifold $L = \{H_{i \epsilon 1} = 0\} \subset W = V \oplus V^*$. Suppose that $\{e^{i \epsilon 1}, f_{i \epsilon 1}\}$ and $\{x^{i \epsilon 1}, y_{i \epsilon 1}\}$ are the given canonical basis and canonical coordinates of $W$ respectively. As we have mentioned in Remark 2.2.29, the vector subspace $V \subset W$, with a basis $\{e^{i \epsilon 1}\}$, is a Lagrangian complement of $T_0 L = \{\sum_{i \epsilon 1} x^i f_i\} \subset W$. But $V$ is not a unique Lagrangian complement of $T_0 L$. Any other Lagrangian complement $\bar{V} \subset W$ of $T_0 L$ corresponds to the change of a canonical basis $\{e^{i \epsilon 1}, f_{i \epsilon 1}\} \mapsto \{\bar{e}^{i \epsilon 1}, \bar{f}_{i \epsilon 1}\}$, $\bar{e}^i := e^i + \sum_{j \epsilon 1} s^{ij} f_j$, $\bar{f}_i := f_i$ of $W$, where $(s^{ij}) : V \otimes V \rightarrow C$ is an arbitrary symmetric tensor. Note that $\{\bar{e}^{i \epsilon 1}\}$ is a new basis spanning the new Lagrangian complement $\bar{V}$ of $T_0 L$ which remains fixed. The corresponding change of canonical coordinates on $W$ is given by $\bar{x}^i = x^i - \sum_{j \epsilon 1} s^{ij} y_j$, $\bar{y}_i = y_i$.

The symplectic form retains its canonical form $\Omega = \sum_{i \epsilon 1} dx^i dx^j$, in this new coordinates and $T_0 L \cong W/\bar{V} \approx \bar{V}$, therefore $W \cong \bar{V} \oplus \bar{V}^*$. Expressing the Airy structure $\{H_{i \epsilon 1}\}$ using the new coordinates $\{\bar{e}^{i \epsilon 1}, y_{i \epsilon 1}\}$ in the usual form (2.19) we obtain the new tensors $\bar{A} = (a_{ij}), \bar{B} = (b_{ij}), \bar{C} = (c_{ik})$.

Both Airy structures $(V, A, B, C)$ and $(\bar{V}, \bar{A}, \bar{B}, \bar{C})$ are the same in the sense that they define the same Lagrangian submanifold $L \subset W$, but we have chosen to described them differently using the different choices of Lagrangian complement $\bar{V}$. Hence we call $(V, A, B, C) \mapsto (\bar{V}, \bar{A}, \bar{B}, \bar{C})$ a gauge transformation of Airy structures.

We can also explore gauge transformation associate with freedom in choosing a basis $\bar{e}^i := \sum_{j \epsilon 1} d^i_j e^j$ of $V$ and $\bar{f}_i := \sum_{j \epsilon 1} c^i_j f_j$ of $V^*$. The corresponding change of coordinates given by $\bar{x}^i = \sum_{j \epsilon 1} d^i_j x^j$ and $\bar{y}_i = \sum_{j \epsilon 1} c^i_j y_j$ respectively. We require $(c^i_j) : V \rightarrow V$ and $(d^j_i) : V \rightarrow V$ to be the inverse of each other, i.e. $\sum_{k \epsilon 1} d^i_k c^k_j = \delta^i_j$ and $\sum_{k \epsilon 1} c^i_k d^j_k = \delta^j_i$, so that the coordinates $\{\bar{x}^{i \epsilon 1}, \bar{y}_{i \epsilon 1}\}$ remain canonical for $W = V \oplus V^*$. Let us also redefine the basis for $g = \bigoplus_{i \epsilon 1} C \cdot H_i$ by $H_i \mapsto H_i := \sum_{j \epsilon 1} c^i_j H_j$. The commutation relations become

$$\{H_i, H_j\} = \bar{g}^{k}_{ij} H_k, \quad \text{where} \quad \bar{g}^{k}_{ij} := g^{k}_{ij} c^i_j c^k_i d^j_i.$$

Here and the remaining of this section, Einstein summation notations will be used where appropriate. Note that $\bar{g}^{k}_{ij} := g^{k}_{ij} c^i_j c^k_i d^j_i$ only involve finite summations since $g^{k}_{ij}$ are components of the tensor $\{g^{k}_{ij}\} : V \rightarrow V \otimes V$ as explained in Remark 2.2.16 (see also Remark 2.2.12). Hence $\bar{g}^{k}_{ij}$ is well-defined and we have a tensor $\{\bar{g}^{k}_{ij}\} : V \rightarrow V \otimes V$.

Remark 2.2.28 For a fixed $i \in I$, $c^i_j$ will be non-zero for only finitely many $j \in I$. It follows that the elements of the inverse matrix must satisfy the same properties. Namely, given an $i \in I$, $d^i_j$ will be non-zero for only finitely many $j \in I$. On the other hand, $s^{ij}$ can be non-zero for infinitely many pairs of $(i, j) \in I^2$.

As a summary, let us give an explicit formula for the gauge transformation $(V, A, B, C) \mapsto (\bar{V}, \bar{A}, \bar{B}, \bar{C})$ associating with the change of a canonical basis $\{e^{i \epsilon 1}, f_{i \epsilon 1}\} \mapsto \{\bar{e}^{i \epsilon 1}, \bar{f}_{i \epsilon 1}\}$ of $W$:

$$\bar{e}^i := \sum_{j \epsilon 1} d^i_j \left( e^j + \sum_{k \epsilon 1} s^{jk} f_k \right), \quad \bar{f}_i := \sum_{j \epsilon 1} c^i_j f_j, \quad (2.27)$$

where $(e^j) : V \rightarrow V$ and $(d^i_j) : V \rightarrow V$ are the inverse of each other and $(s^{ij}) : V \times V \rightarrow C$. It is easy to check that

$$\Omega(\bar{e}^i, \bar{e}^j) = \Omega(\bar{f}_i, \bar{f}_j) = 0, \quad \Omega(\bar{e}^i, \bar{f}_j) = \delta^i_j.$$

The corresponding change of a canonical coordinates is given by:

$$\bar{x}^i := \sum_{j = 1}^{\infty} d^i_j \left( x^j - \sum_{k = 1}^{\infty} s^{jk} y_j \right), \quad \bar{y}_i := \sum_{j = 1}^{\infty} c^i_j y_j, \quad (2.28)$$
and it is easy to check that
\[ \{ \hat{x}^i, \hat{x}^j \} = \{ \hat{y}_i, \hat{y}_j \} = 0, \quad \{ \hat{y}_i, \hat{x}^j \} = \delta_i^j. \]

Denote the transformation (2.27) by \( T : W \to W \). Let \( \tilde{V} \subset W \) be the vector subspace spanned by \( \{ \hat{\epsilon}^{\hat{e}}� \} \):
\[
\tilde{V} := T(V). \tag{2.29}
\]

Substituting the inverse coordinates transformation \( x^i = \sum_{j,k} (c_j^i \hat{x}^j + \sum_k y_{ij} d_k \hat{s}^{ki}) \), \( y_i = \sum_{j,k} d_i^j \hat{y}_j \), into (2.19) and collecting terms so that \( \hat{H}_i := \sum_{j,k} c_i^j H_j \) takes the form
\[
\hat{H}_i := -\hat{y}_i + \sum_{j,k} a_{ijk} \hat{x}^j \hat{x}^k + 2 \sum_{j,k} b_{ijk} \hat{x}^j \hat{y}_k + \sum_{j,k} c_{ijk} \hat{y}_j \hat{y}_k,
\]

we find that \((V, A, B, C, \epsilon) \mapsto (\tilde{V}, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\) is given by [25, Section 2.1]
\[
\tilde{a}_{ij12} := a_{ij12} c_{ij12} \tilde{a}_{ij12}, \tag{2.30}
\]
\[
\tilde{b}_{ij12} := b_{ij12} c_{ij12} \tilde{b}_{ij12}, \tag{2.31}
\]
\[
\tilde{c}_{ij12} := c_{ij12} c_{ij12} \tilde{c}_{ij12}, \tag{2.32}
\]

Similarly, we study gauge transformations of quantum Airy structures \((V, A, B, C, \epsilon) \mapsto (\tilde{V}, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\) by making the following substitutions:
\[
x^i \mapsto \hat{x}^i := \sum_{j,k} \left( c_j^i \hat{x}^j + \sum_k s^{ik} d_k \hat{h} \hat{\partial}_j \right), \quad \hat{h} \partial_j = h \partial x^i \mapsto \hat{y}_i := \sum_{j,k} d_i^j \hat{h} \partial_j = \sum_{j,k} d_i^j \partial_j \hat{y}_j + h \tilde{\epsilon}_i.
\]

in (2.20) and collecting terms so that \( \tilde{\hat{H}} := \sum_{j,k} c_i^j \tilde{H}_j \) takes the form:
\[
\tilde{\hat{H}}_i := -h \hat{\partial}_i + \sum_{j,k} a_{ijk} \hat{x}^j \hat{x}^k + 2h \sum_{j,k} b_{ijk} \hat{x}^j \hat{\partial}_k + h^2 \sum_{j,k} c_{ijk} \hat{\partial}_j \hat{\partial}_k + h \tilde{\epsilon}_i.
\]

We find that the transformation \( A \mapsto \tilde{A}, B \mapsto \tilde{B}, C \mapsto \tilde{C} \) are given by (2.30)-(2.32) and \( \epsilon \mapsto \tilde{\epsilon} \) is given by [25, Section 2.2]
\[
\tilde{\epsilon}_i := \epsilon_i c_i^{\hat{e}} + a_{ijk} \epsilon_i c_k^{\hat{e}}, \tag{2.33}
\]

Because the commutation relations of \( \hat{x}^i \) and \( \hat{y}_j \) in \( \mathcal{D}^0(W) \) are the same as those of \( x^i \) and \( h \hat{\partial}_j \), we conclude that \((V, A, B, C, \epsilon)\) is a quantization of \((\tilde{V}, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\).

**Remark 2.2.29** Suppose that \((V, A, B, C, \epsilon)\) is a quantum pre-Airy structure. Given \((c_i^\hat{e}) : V \to V, (d_i^\hat{e}) = (c_i^\hat{e})^{-1} : V \to V\) and \((s^{\hat{e}j}) : V \times V \to C\), then \((V, A, B, C, \epsilon) \mapsto (\tilde{V}, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\) given by (2.29)-(2.33) is also a quantum pre-Airy structure transformation. We call this a gauge transformation of quantum pre-Airy structure.

**Remark 2.2.30** The gauge transformation respects sub-structures in the following sense [25, Section 2.6]. We write \( \tilde{V} := T(V) \). Suppose that \((U, A, B, C, \epsilon)\) is a quantum (pre-)Airy sub-structure of \((V, A, B, C, \epsilon)\) then \((U, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\) is a quantum (pre-)Airy sub-structure of \((\tilde{V}, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{\epsilon})\) where \( U := T(U) \) and \( T : W \to W \) denotes the transformation (2.27).

**2.3 The Residue Constraints Airy Structure**

In this section, we are going to review the residue constraints Airy structure [25, Section 3.3]. It is the Airy structure that will be most interesting to us due to its connection with topological recursion as we will explain in Section 2.6. Consider a countably infinite dimensional (let \( L := \mathbb{Z}_{>0} \)) vector space
\[
V_{Airy} := z^{-1} \mathbb{C}[z^{-1}] \frac{dz}{z}
\]
of meromorphic differential forms in the neighborhood of \( z = 0 \) and equipped with the discrete topology. The set \( \{ \epsilon^k \hat{e} := z^{-k} \frac{dz}{z} \} \) is a basis of \( V_{Airy} \). The continuous dual space is given by
\[
V_{Airy} := \mathbb{C}[\mathbb{C}][z] \frac{dz}{z}
\]
where a vector \( f \in V_{\text{Airy}} \) can be thought of as a linear functional \( v \mapsto \text{Res}_{z=0}(f \int v) \in \mathbb{C} \) on \( V_{\text{Airy}} \). The set \( \{ f_{k \in \mathbb{C}} := k z^k \frac{dz}{z} \} \) is a basis of \( V_{\text{Airy}}^* \), we can check that \( f_i(e^j) = \delta_{i,j} \). The corresponding Tate space is

\[
W_{\text{Airy}} := V_{\text{Airy}} \oplus V_{\text{Airy}}^* = \{ \eta \in \mathbb{C}(z)dz \mid \text{Res}_{z=0} \eta = 0 \}
\]

with the symplectic form

\[
\Omega_{\text{Airy}}(f, g) := \text{Res}_{z=0} \left( f \int g \right).
\]

Any typical element \( w \) of \( W_{\text{Airy}} \) can be expressed as \( w := \sum_{k \in \mathbb{C}} \left( x^k f_k + y_k e^k \right) = \sum_{k=1}^{\infty} \left( y_k z^{-k} \frac{dz}{z} + k x^k z^{-k} \frac{dz}{z} \right) \), where \( y_k \in \mathbb{C} \) is non-zero for an only finite number of \( k \). The symbol \( f \int g \) in the definition of \( \Omega_{\text{Airy}}(f, g) \) denotes a formal indefinite integral of \( g \). For instance, let us write \( g := \sum_{k=1}^{\infty} \left( y_k z^{-k} \frac{dz}{z} + k x^k z^{-k} \frac{dz}{z} \right) \) then \( f := \sum_{k=1}^{\infty} \left( -\frac{1}{2} y_k z^{-k} + k x^k \frac{dz}{z} \right) + \text{const} \). Note that the integration constant does not introduce any ambiguity in the expression of \( \Omega_{\text{Airy}}(f, g) \) since the residue of \( f \) is zero. It is easy to check that \( f \mapsto \Omega_{\text{Airy}}(f, \cdot) \) gives an isomorphism \( W \cong W^* \) and in particular, \( e^k \mapsto \Omega_{\text{Airy}}(e^k, \cdot) \) gives an isomorphism \( V_{\text{Airy}} \cong V_{\text{Airy}}^* \).

Define the residue constraints Airy structure \( \{ H_{\infty} \} \) on \( V_{\text{Airy}} \) by

\[
(H_{\text{Airy}})_{2n}(w) = \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right) z^{2n} d(z^2) \right),
\]

\[
(H_{\text{Airy}})_{2n-1}(w) = \frac{1}{2} \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right) z^{2n-2} d(z^2) \right), \quad n = 1, 2, 3, ...
\]

(2.34)

where \( w(z) := \sum_{k \in \mathbb{C}} \left( x^k f_k + y_k e^k \right) = \sum_{k=1}^{\infty} \left( y_k z^{-k} \frac{dz}{z} + k x^k z^{-k} \frac{dz}{z} \right) \in W_{\text{Airy}} \). By expanding \( \Omega_{\text{Airy}}(\cdot, h) \) into formal polynomials in \( \text{Sym}_{\leq 3}(W_{\text{Airy}}) \) of coordinates \( \{ x^{\infty}, y_{\infty} \} \) of \( W_{\text{Airy}} \), we find that \( \{ (H_{\text{Airy}})_{\infty} \} \) can be expressed in the standard form [25, Section 3.3]:

\[
(H_{\text{Airy}})_{2n} = -J_{2n}, \quad (H_{\text{Airy}})_{2n-1} = -J_{2n-1} + \frac{1}{4} \sum_{k=-\infty}^{\infty} J_{2k-1} J_{2n-2k-3}, \quad n = 1, 2, 3, ...
\]

(2.35)

where \( J_{2k} := y_k, J_{-2k} := k x^k \). The quantization of Airy structure \( \{ (H_{\text{Airy}})_{\infty} \} \) exists and it is given by [25, Section 3.3]

\[
(H_{\text{Airy}})_{2n} = -\hat{J}_{2n}, \quad (H_{\text{Airy}})_{2n-1} = -\hat{J}_{2n-1} + \frac{1}{4} \sum_{k=-\infty}^{\infty} \hat{J}_{2k-1} \hat{J}_{2n-2k-3} + \frac{h}{16} \delta_{n,2}, \quad n = 1, 2, 3, ...
\]

(2.36)

where \( \hat{J}_{2k} := h \frac{\partial}{\partial x^k}, \hat{J}_{-2k} := k x^k \). By reading the coefficients of [2.36], we found that the tensors \( A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}} \) and \( \epsilon_{\text{Airy}} \) are given by [25, Section 3.3]

\[
A_{\text{Airy}} = \frac{1}{4} \epsilon^1 \otimes \epsilon^1 \otimes \epsilon^1, \quad \text{or} \quad (a_{\text{Airy}})_{ijk} = \frac{1}{4} \delta_{ij} \delta_{lj} \delta_{lk}
\]

(2.37)

\[
B_{\text{Airy}} : e^n \mapsto \frac{1}{4} \sum_{n_1 + n_2 = n + 3 \atop n_1 \text{ odd}} n_2 e^{n_1} \otimes e^{n_2}, \quad \text{or} \quad (b_{\text{Airy}})^k_l = \frac{1}{4} \sum_{k_1 + k_2 = k + 3 \atop k_1 \text{ odd}} k_2 \delta_{k_1} \delta_{k_2}
\]

(2.38)

\[
C_{\text{Airy}} : e^{n_1} \otimes e^{n_2} \mapsto \begin{cases} 0, & n_1 + n_2 \text{ odd} \\
\frac{1}{4} e^{n_1+n_2+3}, & n_1 + n_2 \text{ even}
\end{cases}, \quad \text{or} \quad (c_{\text{Airy}})^k_j = \begin{cases} 0, & j + k \text{ odd} \\
\frac{1}{4} \delta_{k,j+k+3}, & j + k \text{ even}
\end{cases}
\]

(2.39)

\[
\epsilon_{\text{Airy}} = \frac{1}{16} \epsilon^3, \quad \text{or} \quad (\epsilon_{\text{Airy}})_{i} = \frac{1}{16} \delta_{i,3}.
\]

(2.40)

Remark 2.3.1 We can also express \( A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}} \) tensors in term of a residue of meromorphic forms by substituting \( w(z) := \sum_{k \in \mathbb{C}} \left( x^k f_k(z) + y_k e^k(z) \right) \) into \( \Omega_{\text{Airy}} \):

\[
(a_{\text{Airy}})_{ijk} = \text{Res}_{z=0} \left( -\frac{1}{4z(dz)^2} f_i(z) f_j(z) f_k(z) \right) \delta_{i, \text{odd}}
\]

\[
(b_{\text{Airy}})^k_l = \text{Res}_{z=0} \left( -\frac{1}{4z(dz)^2} f_i(z) f_j(z) e^k(z) \right) \delta_{i, \text{odd}}
\]

\[
(c_{\text{Airy}})^k_l = \text{Res}_{z=0} \left( -\frac{1}{4z(dz)^2} f_i(z) e^j(z) e^k(z) \right) \delta_{i, \text{odd}}.
\]

where \( \delta_{i, \text{odd}} = \sum_{n=1}^{\infty} \delta_{2n-1} \) if \( i \) is an odd integer and \( 0 \) if \( i \) is an even integer. Sometime it is easier to work with \( A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}} \) in this form. It is less straightforward to express \( \epsilon_{\text{Airy}} \) as a residue.
One last important point to note is that \((V_{\text{Airy}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) contains a primitive quantum Airy sub-structure \(((V_{\text{Airy}})_{\text{odd}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) where

\[(V_{\text{Airy}})_{\text{odd}} := z^{-1}C[z^{-2}]\frac{dz}{z}.
\]

### 2.3.1 The Lagrangian ‘submanifold’ \(L_{\text{Airy}} \subset W_{\text{Airy}}\)

As we have mentioned in the last section, the interpretation of an Airy structure as a quadratic Lagrangian submanifold is less obvious when dimension is infinite. Let us show how \(L_{\text{Airy}} := \{(H_{\text{Airy}})_{i=1} = 0\} \subset W_{\text{Airy}}\) highlights this difficulty.

**Lemma 2.3.2**

\[\{w \in W_{\text{Airy}} \mid (H_{\text{Airy}})_{i=1}(w) = 0\} = \{x^1 = y_1 = y_2 = y_3 = \cdots = 0\} \subset W_{\text{Airy}}.\]

In other words, the solution to \((H_{\text{Airy}})_{i=1} = 0\) in \(W_{\text{Airy}}\) are the trivial ones. Therefore, by interpreting \(L_{\text{Airy}}\) as a subset of \(W_{\text{Airy}}\) we will have \(L_{\text{Airy}}\) as a linear subspace of \(W_{\text{Airy}}\) instead of a non-linear submanifold as the name quadratic suggests.

**Proof:** Since \((H_{\text{Airy}})_{2n} = 0\) implies \(y_{2n} = 0\), it remains for us to show that \(x^1 = y_{2n-1} = 0\) for all \(n = 1, 2, 3, \ldots\). Since \(w = \sum_{k=1}^{\infty} (y_k z^{-k}\frac{dz}{z} + k x^k z^{-k}\frac{dz}{z}) \in W_{\text{Airy}}\) means there are finitely many non-zero \(y_{i}\)'s, let us assume that \(y_{2n+1} = 0\) for all \(n \geq N\) for some \(N \in \mathbb{Z}_{>0}\). Then it is easy to check that \((H_{\text{Airy}})_{4n+1} = \frac{1}{4}y_{2n-1}^4 = 0\), which implies \(y_{2n-1} = 0\). Therefore \(y_{2n-1} = 0\) for all \(n = 1, 2, 3, \ldots\). Finally, \(y_1 = 0\) implies \((H_{\text{Airy}})_{1} = \frac{1}{4}(x^1)^2 = 0\). Therefore \(x^1 = 0\) and the lemma is proven. \(\square\)

This Lemma tells us that any solution \(w = \sum_{k=1}^{\infty} (y_k z^{-k}\frac{dz}{z} + k x^k z^{-k}\frac{dz}{z}) \) to \((H_{\text{Airy}})_{i=1}(w) = 0\) with \(x^1 \neq 0\) must consist of infinitely many non-zero \(y_{i}\) and so \(w\) does not belong to \(W_{\text{Airy}}\). According to Theorem 2.2.2 or Corollary 2.2.25 there exists \(\psi_{L_{\text{Airy}}} := \exp\left(\sum_{g=0}^{\infty} \hbar^{g-1}(S_{\text{Airy}})_{g}\right)\) such that \((\psi_{L_{\text{Airy}}})^{-1}(H_{\text{Airy}})(\psi_{L_{\text{Airy}}}) = 0\). In particular, we can still find the generating function \((S_{\text{Airy}})_{0}\) such that

\[(H_{\text{Airy}})_{i}\left(\left\{x^{i} \in \mathbb{C}[z]\right\}, \left\{y_{i} \in \mathbb{C}[z]\right\}, \frac{\partial(S_{\text{Airy}})_{0}}{\partial x^i}\right) = 0, \quad i \in \mathbb{I},
\]

although we will have \(\frac{\partial S_{\text{Airy}}}{\partial x^i} \neq 0\) for infinitely many \(i \in \mathbb{I}\). In this sense, \(L_{\text{Airy}}\) can be thought of formally as a Lagrangian submanifold of \(W_{\text{Airy}}\).

Nevertheless, we define \(T_{0}L_{\text{Airy}} := z\mathbb{C}[z] \frac{dz}{z} \subset W_{\text{Airy}}\). It is clear that \(T_{0}L_{\text{Airy}}\) is a Lagrangian subspace of \(W_{\text{Airy}}\) and \(V_{\text{Airy}}\) is a Lagrangian complement of \(T_{0}L_{\text{Airy}}\).

### 2.4 The Embedding of Discs and The Analytic Residue Constraints

Essentially, our work in this section is an analytic approach to [25, Section 6]. As we have seen, the quadratic Lagrangian submanifold \(L_{\text{Airy}} \subset W_{\text{Airy}}\) defined by the residue constraints can only be interpreted formally and not as an actual submanifold. In this section, we will study the residue constraints from an analytic perspective. We show that there exists non-trivial solution \(L_{\text{Airy}} := \{(H_{\text{Airy}})_{i=1,2,3,\ldots} = 0\}\) of residue constraints in a modified version of \(W_{\text{Airy}}\), which will be introduced as \(W_{c.M}^{r,\text{Airy}}\). We also will see how the residue constraints are related to the deformation of discs embedded in the foliated symplectic surface \((\mathbb{C}^2, dx \wedge dy, \{x = \text{const}\})\).

Another motivation for us to take the analytic approach instead of the formal one is because it should make the connection between Airy structures and the prepotential \(\delta\Sigma_{\omega}\) more transparent as \(\delta\Sigma_{\omega}\) is a holomorphic function.

We organize the content of this section as follows. In Section 2.4.1 we introduce the space of analytic discs \(\text{Discs}^{M}\) (similar to the space of formal discs \(\text{Discs}\) in [25, Section 6]) and the vector bundle \(W^{c.M} \rightarrow \text{Discs}^{M}\). Some interesting properties of \(W^{c.M}\) will be noted. In Section 2.4.2 we show how the residue constraints Airy structure can be considered analytically. For example, when writing \((H_{\text{Airy}})_{i}\) in the standard form (2.19), all summations converge absolutely and there is no ambiguity in summation order. On the other hand, not all gauge transformations considered in Section 2.2.4 are allowed in the analytic context, and we propose a more restricted class of gauge transformations. We also explore how some of the analytic solutions in \(L_{\text{Airy}}^{M}\) can be expressed in terms of the genus zero part of the ATR with quantum Airy structure \((V_{\text{Airy}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}})\).
which we have discussed previously as a formal power series. Finally, we define in Section 2.4.3 an embedding map $\Phi_{t_0} : Discs_{t_0}^{c,M} \to W_{t_0}^{c,M}$ analogous to $\Phi_{s_0} : B_{s_0} \to H_{s_0}$ defined in Section 2.1 and show that the image of $\Phi_{t_0}$ is given by convergence Laurent series satisfying the residue constraints.

2.4.1 The space of discs

We begin by introducing the notion of analytic discs and the trivial weak symplectic vector bundle $(W^{c,M} \to Discs^{M}, \Omega, \nabla)$. Unlike the formal discs and symplectic vector bundle $W \to Discs$ introduced in [25, Section 6], the convergence condition of series on some annulus will be enforced in our version. The upshot is that $(W^{c,M} \to Discs^{M}, \Omega, \nabla)$ is flat (Lemma 2.4.12), covariantly constant (Lemma 2.4.14) and the parallel transport of $\xi_1 \in W_{t_1}^{c,M}$ to $W_{t_2}^{c,M}$, for any two points $t_1, t_2 \in Discs^{M}$ sufficiently close, is given by (Lemma 2.4.13)

$$\xi_2 := \exp \left( (a(t_2) - a(t_1))L_{\frac{\partial}{\partial t}} \right)(\xi_1) \in W^{c,M},$$

where $\exp(aL_{\frac{\partial}{\partial t}})$ is an operator exponential of the Lie derivative $\frac{\partial}{\partial t}$. If $|a(t_2) - a(t_1)|$ is too large then $\xi_2$ may not have the desired convergence properties to be in $W_{t_2}^{c,M}$. This is why it is important for $t_1$ and $t_2$ to be sufficiently close. In fact, most of the contents from Lemma 2.4.9 until Lemma 2.4.12 are dedicated to discussing the properties of $\exp(aL_{\frac{\partial}{\partial t}})$ and in particular, the precise notion for $t_1$ and $t_2$ to be considered ‘sufficiently close’. However, these details are technical and can be skipped in the first reading. On the other hand, Lemma 2.4.13 is the key result that will be used in the construction of $\Phi_{t_0} : Discs_{t_0}^{c,M} \to W_{t_0}^{c,M}$ later in Section 2.4.3.

In the simplest terms, a disc is an embedding $t : D \cong \mathbb{D} \hookrightarrow \mathbb{C}$ such that $\mathbb{D}_t$ has a tangency of order 1 to a leaf of the foliation at $r := t(0)$, where $\mathbb{D} \subset \mathbb{C}$ is an open neighbourhood of 0 ∈ $\mathbb{C}$. Using the standard local coordinate $z := \sqrt{x - x(r)}$, in general, the embedding $t$ is a parameterization of $\mathbb{D}_t \subset \mathbb{C}$ which can be written in the form

$$t = (x = a + z^2, y = b_0 + b_1 z + b_2 z^2 + b_3 z^3 + ...)$$

where $b_k \neq 0$. The study of the embedding of discs helps us understand at the local level the deformation of $F$-transversal curves $\Sigma$ embedded inside a foliated symplectic surface $(S, \Omega, F)$. As explained in Section 2.1, given a curve $[\Sigma] \in B$ then we can find a $(F, \Omega_\Sigma)$-chart $U_\Sigma$ around any ramification point $r_\alpha, \alpha \in \text{Ram of } \Sigma$. Because $U_\Sigma$ is symplectomorphic to an open subset of the foliated symplectic surface $(\mathbb{C}^2, dx \wedge dy, \{x = \text{const}\})$, therefore $\Sigma \cap U_\Sigma$ can be treated as a disc embedded in $(\mathbb{C}^2, dx \wedge dy, \{x = \text{const}\})$. We will compare the global deformation of $\Sigma \subset S$ to the deformation of discs embedded around each ramification point of $\Sigma$ later in Section 2.5.

Because discs are only defined locally, it follows that their deformation space is much larger than that of a $F$-transversal curve $\Sigma$. Let us now define the space of discs:

**Definition 2.4.1** Let $Discs := \{z \in \mathbb{C} \mid |z| < M\}$, then

$$Discs^M := \left\{ t : \mathbb{D} \cong \mathbb{D} \hookrightarrow \mathbb{C}^2 \mid t = (x = a(t) + z^2, y = \sum_{k=0}^{\infty} b_k(t)z^k), \sum_{k=0}^{\infty} b_k(t)z^k \text{ converges for } |z| < M \text{ for some } M < \bar{M}. \right\}.$$

We can think of $Discs^M$ as a subset of the infinite dimensional vector space of infinite tuple of numbers $(a(t), b_0(t), b_1(t), \ldots)$. It is almost a vector subspace except for the condition $b_1(t) \neq 0$. Nevertheless, for $t_1, t_2 \in Discs^M$ and $\lambda_1, \lambda_2 \in \mathbb{C}$ such that $\lambda_1 b_1(t_1) + \lambda_2 b_1(t_2) \neq 0$ we define

$$\lambda_1 t_1 + \lambda_2 t_2 := (x = \lambda_1 a(t_1) + \lambda_2 a(t_2) + z^2, y = \sum_{k=0}^{\infty} (\lambda_1 b_k(t_1) + \lambda_2 b_k(t_2))z^k) \in Discs^M.$$

We define the kinematic tangent space $T_1Discs^M$ as guided by [26]:

$$T_1Discs^M := \left\{ v = A \frac{\partial}{\partial a} + \sum_{k=0}^{\infty} B_k \frac{\partial}{\partial b_k} \mid A, B_k \in \mathbb{C}, \sum_{k=0}^{\infty} B_k z^k \text{ converges for } |z| < M \text{ for some } M < \bar{M}. \right\}.$$

More precisely, $T_1Discs^M$ is the set of $v \in Discs^M$ such that $\gamma(t) := t + tv$ defines a path $\gamma : (-\delta, \delta) \to Discs^M$ for some $\delta > 0$. The tangent space $T_1Discs^M$ tells us information about the infinitesimal deformations of $\mathbb{D}_t$.

We are going to introduce the vector bundle $W^{c,M} \to Discs^M$ which can be thought of as a local counter-part of the vector bundle $\mathcal{H} \to B$ defined in Section 2.1. A fiber of $W^{c,M}$ over each point $t \in Discs^M$ is given by $W_{Airy}^{c,M}$, the analytic version of $W_{Airy}$. Unlike $W_{Airy}$ which is a symplectic topological vector space, $W_{Airy}^{c,M}$ will be a weak symplectic vector space.
Definition 2.4.2 A weak symplectic (topological) vector space \((W, \Omega)\) is a pair of a (topological) vector space \(W\) and a (continuous) antisymmetric bilinear form \(\Omega: W \times W \to \mathbb{C}\) such that \(w \mapsto \Omega(w,.)\) is injective \(W \hookrightarrow W^*\). We call \(\Omega\) the weak symplectic form of \(W\).

Definition 2.4.3 For any \(\epsilon, M \in \mathbb{R}\) such that \(0 < \epsilon < M\), the weak symplectic vector space \((W^\epsilon,M, \Omega_{Airy})\) is given by
\[
W^\epsilon,M_{Airy} := \left\{ \xi \in z^{-1}\mathbb{C}[z^{-1}] \left[ \frac{dz}{z} \right] \right\}
\]
and the symplectic form \(\Omega_{Airy}\) is given by:
\[
\Omega_{Airy}(\xi_1, \xi_2) := Res_{z=0} \left( \int \xi_2 - \frac{dz}{z} \right).
\]

The definition of the symplectic form \(\Omega_{Airy}\) is exactly the same as the one on \(W_{Airy}\), hence we are denoting them using the same notation. Let \((W^\epsilon,M \to Discs^M, \Omega, \nabla)\) be the trivial weak symplectic vector bundle, \(W^\epsilon,M := Discs^M \times W^\epsilon,M_{Airy}\). The fiber over each point \(t \in Discs^M\) of \(W^\epsilon,M\) is given by the weak symplectic vector space \((W^\epsilon,M_t, \Omega_t) := (W^\epsilon,M_{Airy})\). The connection \(\nabla\) is given by:
\[
\nabla := d - (da)\mathcal{L}_{\frac{1}{z} \partial_a} = da \frac{\partial}{\partial a} + \sum_{k=0}^{\infty} db_k \frac{\partial}{\partial b_k} - (da)\mathcal{L}_{\frac{1}{z} \partial_z}.
\]

Remark 2.4.4 The following are useful elementary facts when working with any \(\xi \in W^\epsilon,M_{Airy}\). If a Laurent series \(\sum_{k=-\infty}^{\infty} a_kz^k\) converges for \(\bar{\epsilon} < |z| < \bar{M}\) then it converges absolutely and uniformly for \(\epsilon < |z| < M\) for any \(\epsilon > \bar{\epsilon}\) and \(M > \bar{M}\). From the uniform convergence, it follows that the integration of a Laurent series can be done term-by-term. Similarly, using the Cauchy integral formula, we find that the differentiation of a Laurent series can also be done term-by-term.

Remark 2.4.5 Let us explain why the symplectic form \(\Omega_{Airy} : W^\epsilon,M_{Airy} \times W^\epsilon,M_{Airy} \to \mathbb{C}\) is well-defined. If \(\xi_2 = \sum_{k=1}^{\infty} (y_2_k)z^{-k} \frac{dz}{z} + (x_2_k)z^k \frac{dz}{z}\) converges to a holomorphic differential on an annulus \(\bar{\epsilon} < |z| < \bar{M}\) with \(\epsilon < \bar{\epsilon} < M < \bar{M}\) then the indefinite integral \(\int \xi_2\) converges to a holomorphic function on the same annulus. It follows that \(\xi_1 \int \xi_2\) is holomorphic on some annulus containing \(\epsilon < |z| < M\) and hence its residue is well-defined as a coefficient of \(\frac{1}{z}\) in the Laurent expansion of \(\xi_1 \int \xi_2\). The integration constant arising from \(\int \xi_2\) will not introduce any ambiguity in \(Res_{z=0}(\xi_1 \int \xi_2)\) because the residue of \(\xi_1\) is zero.

Remark 2.4.6 It is possible to assign a topology to \(W^\epsilon,M\). For example, we can equip \(Discs^M\) and \(W^\epsilon,M\) with the topology induced from the following norms:
\[
\|t\|_{Discs^M} := \left\| a(t) \right\|^2 + \left( \sup_{\epsilon < |z| < M} \left| \sum_{k=0}^{\infty} b_k(t)z^k \right| \right); \quad \|\xi\|_{W^\epsilon,M} := \sup_{\epsilon < |z| < M} \left| \xi(z) \frac{dz}{z} \right|
\]
and equip \(W^\epsilon,M := Discs^M \times W^\epsilon,M_{Airy}\) with the product topology. The topology of \(W^\epsilon,M\) will play no role later. Note that for \(W^\epsilon,M_{Airy}\) to be a weak symplectic vector space, a topology is not needed. The stronger condition of symplectic requires a topology because an infinite-dimensional vector space is always strictly smaller than its algebraic dual, hence a topology is needed for the condition \(W \cong W^*\) to be satisfied. The fact that \(W_{Airy}\) is weak symplectic instead of symplectic will not lead to any major consequences.

Remark 2.4.7 We follow [25, 27] in defining a connection \(\nabla\) (as given in (2.41)) on an infinite-dimensional vector bundle over an infinite-dimensional manifold. Let us explain more precisely the meaning of \(\Gamma(Discs^M, W^\epsilon,M)\) and \(\Gamma(Discs^M, Hom(TDiscs^M, W^\epsilon,M))\) as follows.
We call a section $\xi$ of $W^{r,M}$ differentiable if $t_{*}\xi d\xi = A_{\frac{\partial }{\partial z}}^\xi + \sum_{k=0}^{\infty} B_{k}^{\xi} \frac{\partial^{k}}{\partial z^{k}} \in W^{r,M}$ for all $v := A_{\frac{\partial }{\partial z}}^v + \sum_{k=0}^{\infty} B_{k}^{v} \frac{\partial^{k}}{\partial z^{k}} \in T_{x}Discs^{M}$ and call $\xi$ smooth if it is infinitely differentiable. We define $\Gamma(Discs^{M}, W^{r,M})$ to be the set of smooth global sections of $W^{r,M}$. Let $\Gamma(Discs^{M}, TDiscs^{M})$ be the set of sections $t \mapsto A(t) \frac{\partial }{\partial a} + \sum_{k=0}^{\infty} B_{k}(t) \frac{\partial^{k}}{\partial a^{k}} \in T_{x}Discs^{M}$ such that $\sum_{k=0}^{\infty} B_{k}(t) z^{k} dx \in \Gamma(Discs^{M}, W^{r,M})$. Finally, we let $\Gamma(Discs^{M}, Hom(TDiscs^{M}, W^{r,M}))$ be a set of linear maps $\Gamma(Discs^{M}, TDiscs^{M}) \rightarrow \Gamma(Discs^{M}, W^{r,M})$.

The term $\mathcal{L}_{\frac{\partial }{\partial a}}$ in the definition of $\nabla$ naturally arises from the deformation of discs via the variation of $a$ keeping the coordinate $x \in \mathbb{C}^{2}$ constant. This is because $x = z^2 + a$. Therefore, the connection $\nabla$ of $W^{r,M}$ is indeed the local version of $\nabla_{GM}$ on $\mathcal{H}$.

Let us examine the operator $\mathcal{L}_{\frac{\partial }{\partial a}}$ more closely. In general, we have that $\mathcal{L}_{h(z)\frac{\partial }{\partial a}} \in End(W_{\mathcal{A}iry}^{r,M})$ for any $h(z) \in \mathbb{C}[z^{-1}] \subset \mathbb{C}[z]$ which converges absolutely for $\bar{\epsilon} < |z| < \bar{M}$ for some $\bar{\epsilon} < \epsilon < M < \bar{M}$. To see this, let $\xi = f(z) \frac{\partial }{\partial a} \in W_{\mathcal{A}iry}^{r,M}$ be given such that $f(z)$ converges absolutely for $\bar{\epsilon} < |z| < \bar{M}$ for some $\bar{\epsilon} < \epsilon < M < \bar{M}$. Then the Lie derivative

$$L_{h(z)\frac{\partial }{\partial a}} \xi(z) = (dt_{h(z)\frac{\partial }{\partial a}} + t_{h(z)\frac{\partial }{\partial a}} d)(f(z) dx) = d(h(z) f(z))$$

is holomorphic for $\bar{\epsilon} < |z| < Min(\bar{M}, M)$. The Laurent series expansion of $L_{h(z)\frac{\partial }{\partial a}} \xi(z)$ also will not have the $\frac{dx}{dz}$ term because $L_{h(z)\frac{\partial }{\partial a}} \xi(z) = (d(h(z) f(z))$ is a total differential and we have $\xi_{|z=\bar{M}} L_{h(z)\frac{\partial }{\partial a}} \xi(z) = 0$. This shows us that $L_{h(z)\frac{\partial }{\partial a}} \xi(z) \in W_{\mathcal{A}iry}^{r,M}$.

For any $a \in \mathbb{C}$, we also define an exponential operator $\exp(aL_{h(z)\frac{\partial }{\partial a}})$ by

$$\exp(a L_{h(z)\frac{\partial }{\partial a}})(\xi) := \sum_{k=0}^{\infty} \frac{a^k}{k!} (L_{h(z)\frac{\partial }{\partial a}})^k(\xi), \quad \xi \in W_{\mathcal{A}iry}^{r,M}$$

The operator $\exp(aL_{h(z)\frac{\partial }{\partial a}})$ can be interpreted as a flow after ‘time’ $a \in \mathbb{C}$ generated by $L_{h(z)\frac{\partial }{\partial a}}$. Note that although $L_{h(z)\frac{\partial }{\partial a}} \in End(W_{\mathcal{A}iry}^{r,M})$, its exponential $\exp(aL_{h(z)\frac{\partial }{\partial a}})$ will not be in $End(W_{\mathcal{A}iry}^{r,M})$ in general. For instance, the flow $\exp(a L_{h(z)\frac{\partial }{\partial a}}) \xi(z) \in W_{\mathcal{A}iry}^{r,M}$ can fail to have the desired convergence properties and ‘fall out’ of $W_{\mathcal{A}iry}^{r,M}$. Let us consider the case where $h(z) := z^k, k \in \mathbb{Z}$ in the following

**Lemma 2.4.9** Given $\xi = f(z) dz(z) \in W_{\mathcal{A}iry}^{r,M}$ converges absolutely for $\bar{\epsilon} < |z| < \bar{M}$ where $\bar{\epsilon} < \epsilon < M < \bar{M}$. Then for $a \in \mathbb{C}$ with a sufficiently small $|a|:

$$|a| < \left\{ \begin{array}{ll}
\min \left( \frac{1-k - \epsilon^{-1}}{1-k}, \frac{M^{1-k} - M^{1-k}}{1-k} \right), & k \neq 1, \\
\log \frac{\bar{\epsilon}}{\epsilon}, \log \frac{\bar{M}}{M}, & k = 1 \end{array} \right. \right.$$ 

we have

$$\exp(a L_{z^k \frac{\partial }{\partial a}}) \xi(z) = \begin{cases}
f \left( (z^{1-k} + (1-k)a)^{\frac{1}{1-k}} \right) dg \left( (z^{1-k} + (1-k)a)^{\frac{1}{1-k}} \right), & k \neq 1 \\
f(\epsilon a^z) dg(\epsilon a^z), & k = 1 \end{cases} \in W_{\mathcal{A}iry}^{r,M}$$

In fact, $\exp(a L_{z^k \frac{\partial }{\partial a}}) \xi(z)$ converges absolutely for

$$\left\{ \begin{array}{ll}
\bar{\epsilon} \epsilon^{-1} |a|^{\frac{1}{1-k}} < |z| < (M^{1-k} - (1-k)|a|)^{\frac{1}{1-k}}, & k \neq 1 \\
\bar{\epsilon} |\epsilon^{a} - 1| < |z| < \bar{M} |\epsilon^{a} - 1|, & k = 1 \end{array} \right.$$ 

**Proof:** For $k \neq 1$ we consider a $z$-plane as a $|k-1|$-fold cover of a $w$-plane where $w := z^{1-k}$. We have $z^k \frac{\partial }{\partial a} = (1-k) \frac{\partial }{\partial w}$ and $L_{z^k \frac{\partial }{\partial a}} = L_{(1-k) \frac{\partial }{\partial w}} = (k-1) \mathcal{L}_{\frac{\partial }{\partial a}}$. For any holomorphic functions $f_{1} = f_{1}(w), f_{2} = f_{2}(w)$ we have $L_{\frac{\partial }{\partial a}}(f_{1}(w) f_{2}(w)) = (L_{\frac{\partial }{\partial a}} f_{1}(w)) f_{2}(w) + f_{1}(w) (L_{\frac{\partial }{\partial a}} f_{2}(w)) = (\partial_{w} f_{1}(w) f_{2}(w) + f_{1}(w) \partial_{a} f_{2}(w))$. We recognize $\exp((k-1) a L_{\frac{\partial }{\partial a}})$ as the shift operator $\exp((1-k)a \frac{\partial }{\partial a}) f_{1}(w) f_{2}(w)) = f_{1}(w) + (1-k)|a| f_{2}(w) + (1-k)a f_{2}(w)$.

Choose a branch for $z$ and write $\xi = f(z) dz(z)$ as a differential form on $w$-plane $\xi = f(w^{1-k}) dg(w^{1-k})$, then

$$\exp(a L_{z^k \frac{\partial }{\partial a}})(f(z) dz(z)) = f \left( (w + (1-k)a)^{\frac{1}{1-k}} \right) dg \left( (w + (1-k)a)^{\frac{1}{1-k}} \right)$$

$$= f \left( (z^{1-k} + (1-k)a)^{\frac{1}{1-k}} \right) dg \left( (z^{1-k} + (1-k)a)^{\frac{1}{1-k}} \right) =: f_{a}(z) dag(z).$$
We have that \( f_\varepsilon(z)dz_\varepsilon(z) \) would be holomorphic on the chosen branch-cut whenever \( \varepsilon < |z^{1-k} + (1 - k)a)\frac{1}{1-k} | < M \) or equivalently \( (z^{1-k} + (1 - k)|a|)\frac{1}{1-k} < |z| < (M^{1-k} - (1 - k)|a|)\frac{1}{1-k} \). The condition \( |a| < \min\left(\frac{1}{1-k}, \frac{M^{1-k} - (1 - k)|a|}{1-k} \right) \) ensures that \( (z^{1-k} + (1 - k)|a|)\frac{1}{1-k} < \epsilon \) and \( (M^{1-k} - (1 - k)|a|)\frac{1}{1-k} > M \). On the other hand, \( (z^{1-k} + (1 - k)a)\frac{1}{1-k} = z(1 + (1 - k)a)\frac{1}{1-k} \) is a well-defined function and can be expanded as a Laurent series converges in \( z \) for \( (1 - k)|a|\frac{1}{1-k} < |z| \) if \( 1 - k > 0 \) and for \( |z| < (1 - k)|a|\frac{1}{1-k} \) if \( 1 - k < 0 \). These conditions automatically follow if \( (z^{1-k} + (1 - k)|a|)\frac{1}{1-k} < |z| < (M^{1-k} - (1 - k)|a|)\frac{1}{1-k} \) since \( (1 - k)|a|\frac{1}{1-k} < (z^{1-k} + (1 - k)|a|)\frac{1}{1-k} \) when \( 1 - k > 0 \) and \( (1 - k)|a|\frac{1}{1-k} > (M^{1-k} - (1 - k)|a|)\frac{1}{1-k} \) when \( 1 - k < 0 \).

Since the series \( \xi \in W^{r,M}_{Airy} \) doesn’t contain the term \( \frac{dz}{z} \), by substituting \( z = w\frac{1}{1-k} \) we also do not have the term \( \frac{1}{1-k} \frac{dw}{w} \) in \( f(w)dg(w) \). The operator \( \exp(aL^{\varepsilon}_{s,\partial}) = \exp((k - 1)aL^{\varepsilon}_{s,\partial}) \) shifts \( w \) to \( w + (k - 1)a \) and will not create the term \( \frac{dz}{z} \) therefore, we do not have the term \( \frac{dz}{z} \) in the Laurent series of \( \exp(aL^{\varepsilon}_{s,\partial})L(z) \).

For \( k = 1 \), we note that \( (L_{s,\partial})^k(z) = z \) and \( \exp(aL^{\varepsilon}_{s,\partial})(L(z)) = f(e^{a}z)dg(e^{a}z) \) follows directly for (2.43). Then we can see that if \( |a| < \min\left(\log \frac{\varepsilon}{\bar{\varepsilon}}, \log \frac{M}{\bar{M}} \right) \) we have \( \varepsilon < |e^{a}z| < M \) whenever \( |e^{a}|^{-1} < \varepsilon < |z| < M < M|e^{a}|^{-1} \)

As an immediate consequence of Lemma 2.4.9, we have the following useful statement:

**Corollary 2.4.10** Let \( k \neq 1 \), \( a \in \mathbb{C} \) and define
\[
\epsilon(a) = (z^{1-k} - (1 - k)|a|)\frac{1}{1-k}, \quad M(a) = (M^{1-k} + (1 - k)|a|)\frac{1}{1-k}.
\]
Then we have \( \exp(aL^{\varepsilon}_{s,\partial}) \in \text{Hom}_{\mathbb{C}}(W^{r,M}_{Airy}, W^{r,M}_{Airy}) \).

**Lemma 2.4.11** Let \( k \in \mathbb{Z} \) then \( L^{s,\partial}_{z,\partial} \in \text{sp}(W^{r,M}_{Airy}) \). Moreover, if \( \xi_1, \xi_2 \in W^{r,M}_{Airy} \) and \( a \in \mathbb{C} \) are given such that \( \exp(aL^{\varepsilon}_{s,\partial})\xi_1, \exp(aL^{\varepsilon}_{s,\partial})\xi_2 \in W^{r,M}_{Airy} \) then
\[
\Omega_{Airy}(\exp(aL^{\varepsilon}_{s,\partial})\xi_1, \exp(aL^{\varepsilon}_{s,\partial})\xi_2) = \Omega_{Airy}(\xi_1, \xi_2).
\]

**Proof:** Using (2.42) it is straightforward to check that
\[
\Omega_{Airy}\left(L^{s,\partial}_{z,\partial}, z^n \frac{dz}{z}, z^n \frac{dz}{z}\right) + \Omega_{Airy}\left(z^n \frac{dz}{z}, L^{s,\partial}_{z,\partial}, z^n \frac{dz}{z}\right) = \Omega_{Airy}\left((m + k - 1)z^{n+k-1} \frac{dz}{z}, z^n \frac{dz}{z}\right) + \Omega_{Airy}\left(z^n \frac{dz}{z}, (n + k - 1)z^{n+k-1} \frac{dz}{z}\right) = 0.
\]
Since differentiation of a power series can be done term-by-term (Remark 2.4.5), it follows that
\[
\Omega_{Airy}(L^{s,\partial}_{z,\partial}, \xi_1, \xi_2) + \Omega_{Airy}(\xi_1, L^{s,\partial}_{z,\partial}, \xi_2) = 0
\]
for any \( \xi_1, \xi_2 \in W^{r,M}_{Airy} \). Therefore \( L^{s,\partial}_{z,\partial} \in \text{sp}(W^{r,M}_{Airy}) \), proving the first part of the Lemma. Using Lemma 2.4.9 we check that \( \frac{d}{da} \exp(aL^{\varepsilon}_{s,\partial})\xi_i = L^{s,\partial}_{z,\partial} \exp(aL^{\varepsilon}_{s,\partial})\xi_i \), \( i = 1, 2 \). It follows that
\[
\frac{d}{da} \Omega_{Airy}(\exp(aL^{\varepsilon}_{s,\partial})\xi_1, \exp(aL^{\varepsilon}_{s,\partial})\xi_2) = \Omega_{Airy}(L^{s,\partial}_{z,\partial} \exp(aL^{\varepsilon}_{s,\partial})\xi_1, \exp(aL^{\varepsilon}_{s,\partial})\xi_2) + \Omega_{Airy}(\exp(aL^{\varepsilon}_{s,\partial})\xi_1, L^{s,\partial}_{z,\partial} \exp(aL^{\varepsilon}_{s,\partial})\xi_2).
\]
Which means \( \Omega_{Airy}(\exp(aL^{\varepsilon}_{s,\partial})\xi_1, \exp(aL^{\varepsilon}_{s,\partial})\xi_2) \) is constant and must equal to its value at \( a = 0 \) which is \( \Omega_{Airy}(\xi_1, \xi_2) \).

For this section, we will only need \( L^{s,\partial}_{z,\partial} \), and its exponentiation when \( k = -1 \). According to Lemma 2.4.9, given \( \xi \in W^{r,M}_{Airy} \) converges absolutely for \( \varepsilon < |z| < M, \bar{\varepsilon} < \epsilon < M < \bar{M} \) and given \( a \in \mathbb{C}, |a| < \min(\varepsilon^2 - \bar{\varepsilon}^2, M^2 - \bar{\varepsilon}^2, M^2) \) we have \( \exp(aL^{\varepsilon}_{s,\partial})\xi(z) = f(\sqrt{z^2 + a})dg(\sqrt{z^2 + a}) \in W^{r,M}_{Airy} \) since it is holomorphic for \( \sqrt{z^2 + |a|} < |z| < \sqrt{M^2 - |a|} \). In particular, it is straightforward to check that
\[
\exp(aL^{\varepsilon}_{s,\partial})\xi(z) = z + \frac{a}{2z} + \sum_{k=2}^{\infty} \frac{a^k (-1)^{k-1}(2k - 3)!!}{2^k z^{2k-1}},
\]
(2.44)
which can be recognized as a Laurent series expansion of $\sqrt{z^2 + a} = z\sqrt{1 + \frac{a}{z^2}}$ for $|z| > \epsilon > \sqrt{|a|}$.

We will now show that the vector bundle $(W^{r,M} \to \text{Discs}^M, \Omega, \nabla)$ is flat and the symplectic form $\Omega$ is $\nabla$-covariantly constant.

**Lemma 2.4.12** The vector bundle $W^{r,M} \to \text{Discs}^M$ with the connection $\nabla$ is flat.

**Proof:** We define the exterior covariant derivative

$$d_\nabla : \Gamma\left(\text{Discs}^M, \text{Hom}\left(\bigwedge^r T\text{Discs}^M, W^{r,M}\right)\right) \to \Gamma\left(\text{Discs}^M, \text{Hom}\left(\bigwedge^{r+1} T\text{Discs}^M, W^{r,M}\right)\right)$$

by

$$d_\nabla \psi := (ds)\xi + (-1)^r s \wedge \nabla(\xi) = (ds)\xi - (-1)^r s \wedge da L_{\frac{\partial}{\partial z}}(\xi)$$

where $\psi = s\xi$, $s \in \Gamma(\text{Discs}^M, \Omega^*_\text{Discs}^M)$ and $\xi \in W^{r,M}$, then extend by linearity. We note that $d_\nabla = \nabla$ for $r = 0$. The condition that $\nabla$ is flat is the same as the vanishing of curvature tensor $R_\nabla = d_\nabla \circ d_\nabla = 0$ and it is easy to check that

$$d_\nabla^2 \psi = (d^2s)\xi - (-1)^{r+1}(ds) \wedge da L_{\frac{\partial}{\partial z}}(\xi) - (-1)^r ds \wedge da L_{\frac{\partial}{\partial z}}(\xi) + s \wedge da \wedge da L_{\frac{\partial}{\partial z}}^2(\xi) = 0.$$

This concludes that $\nabla$ is flat. \qed

**Lemma 2.4.13** Pick $t_1, t_2 \in \text{Discs}^M$ such that $|a(t_1) - a(t_2)|$ is sufficiently small, then the parallel transport of $\xi \in W^{r,M}$ to the fiber $W^{r,M}$ exists, path-independent and given by $\xi_{t_2} = \exp((a(t_2) - a(t_1))L_{\frac{\partial}{\partial z}})\xi$. In fact, $\xi_t = \exp((a(t) - a(t_1))L_{\frac{\partial}{\partial z}})(\xi)$ is a parallel vector field.

**Proof:** The path-independence of the parallel transport follows from the fact that $\nabla$ is flat. The condition that $|a(t_1) - a(t_2)|$ being sufficiently small is needed to ensure that $\exp((a(t_2) - a(t_1))L_{\frac{\partial}{\partial z}})(\xi) \in W^{r,M}_{t_2}$ according to Lemma 2.4.9. Finally, we can check that

$$\nabla \xi_t = da \frac{\partial}{\partial a} \exp((a(t) - a(t_1))L_{\frac{\partial}{\partial z}})\xi - da L_{\frac{\partial}{\partial z}} \exp((a(t) - a(t_1))L_{\frac{\partial}{\partial z}})(\xi) = 0.$$ \qed

**Lemma 2.4.14** The symplectic form $\Omega$ is $\nabla$-covariantly constant.

**Proof:** For any $\xi_1, \eta_1 \in W^{r,M}_{t_1}$ we have from Lemma 2.4.12 that their parallel transport to $W^{r,M}_{t_2}$ are $\xi_2 = \exp((a(t_2) - a(t_1))L_{\frac{\partial}{\partial z}})(\xi_1), \eta_2 = \exp((a(t_2) - a(t_1))L_{\frac{\partial}{\partial z}})(\eta_1) \in W^{r,M}_{t_2}$. Therefore, $\Omega_{t_2}(\xi_2, \eta_2) = \Omega_{t_1}(\xi_1, \eta_1)$ by Lemma 2.4.11. \qed

### 2.4.2 The analytic residue constraints

Observe that the residue constraints Hamiltonians:

$$\left(H_{\text{Airy}}\right)_{2n}(w) = \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right)^{2n} dz^2 \right),$$

$$\left(H_{\text{Airy}}\right)_{2n-1}(w) = \frac{1}{2} \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right)^{2n-2} dz^2 \right), \quad n = 1, 2, 3, ...$$

as given in Section 2.3 is not only well-defined when $w(z) \in W_{\text{Airy}}$, but also when $w(z) \in W^{r,M}_{\text{Airy}}$ is a Laurent series converging on some annulus containing $\epsilon < |z| < M$. Define $L^M_{\text{Airy}} := \{(H_{\text{Airy}})_{i=1,2,3,\ldots} = 0 \} \subset W^{r,M}_{\text{Airy}}$. As we will see later, unlike its counter-part $L_{\text{Airy}} \subset W_{\text{Airy}}$ (see Lemma 2.3.3), the submanifold $L^M_{\text{Airy}}$ contains many non-trivial solutions of $(H_{\text{Airy}})_{i=1,2,3,\ldots} = 0$ because an infinite number of terms with negative power in $z$ is allowed. Define the tangent space to $L^M_{\text{Airy}}$ at any point $p \in L^M_{\text{Airy}}$ by

$$T_p L^M_{\text{Airy}} := \left\{ w \in W^{r,M}_{\text{Airy}} \mid t_w d(H_{\text{Airy}})_i = 0, i = 1, 2, 3, \ldots \right\} \subset W^{r,M}_{\text{Airy}}.$$
In particular,
\[
T_0L^M_{\text{Airy}} := \left\{ \xi \in \mathbb{C}[[z]] \mathbb{C} \mid \xi(z) \text{ converges for } |z| < M \right\} \subset W^r, M_{\text{Airy}}, \quad T_0L^M_{\text{Airy}} \subset T_0L^M_{\text{Airy}} \cong V^r_{\text{Airy}}.
\]
is a Lagrangian subspace of \( W^r, M_{\text{Airy}} \). Let us also define
\[
V^r_{\text{Airy}} := \left\{ \xi \in \mathbb{C}[[z]][z^{-1}] \mathbb{C} \mid \xi(z) \text{ converges for } |z| > \epsilon \right\} \subset W^r, M_{\text{Airy}}, \quad V^r_{\text{Airy}} \subset V^r_{\text{Airy}}.
\]

\( V^r_{\text{Airy}} \) is also a Lagrangian subspace of \( W^r, M_{\text{Airy}} \), in fact, it is a Lagrangian complement of \( T_0L^M_{\text{Airy}} : W^r, M_{\text{Airy}} = V^r_{\text{Airy}} \oplus T_0L^M_{\text{Airy}} \). This is similar to \( W_{\text{Airy}} = V_{\text{Airy}} \oplus V_{\text{Airy}} \), but in this case, \( T_0L^M_{\text{Airy}} \subset (V^r_{\text{Airy}})^* \). We let \( \{ e_i := 1, 2, 3, \ldots, f_k := 1, 2, 3, \ldots \} \) to be a canonical basis of \( W^r_{\text{Airy}} \):
\[
\Omega_{\text{Airy}}(e_i, e_j) = \Omega_{\text{Airy}}(f_i, f_j) = 0, \quad \Omega_{\text{Airy}}(e_i, f_j) = \delta_{ij}.
\]
where \( \{ e_i := 1, 2, 3, \ldots \} \) is a basis of \( V^r_{\text{Airy}} \) and \( \{ f_k := 1, 2, 3, \ldots \} \) is a basis of \( T_0L^M_{\text{Airy}} \).

Among many topics we have discussed regarding Airy structures in Section 2.2, we will mostly be interested in the genus zero ATR output and the gauge transformation in the context of the quantum residue constraints Airy structure introduced in Section 2.3. Since we only have considered these topics from the formal perspective in Section 2.2 and 2.3, the goal of this section is to revisit these topics from an analytical perspective within the context of \( \{(H_{\text{Airy}})_i := 1, 2, 3, \ldots \} \). We will show that most things we have learned previously continue to hold, possibly with some minor adjustments. Most difficulties came from the following: In \( W_{\text{Airy}} \), the Tate topology dictates that the contraction between vectors in \( V_{\text{Airy}} \) and \( V_{\text{Airy}} \) always result in finite sums since vectors in \( V_{\text{Airy}} \) are finite linear combinations of \( \{ e_i \} \). On the other hand, \( W^r_{\text{Airy}} \) is not a Tate space and \( w(z) \in W^r_{\text{Airy}} \) in general can be written as \( w(z) = \sum_{k=1}^{\infty} (y_k z^{-k} d^2 z + k x^k z k dz) \) with infinitely many non-zero \( z^k \) and \( y_k \). It turns out that the lack of finiteness can be replaced with absolute uniform convergence. Here are summaries of the key points:

1. By expressing \( (H_{\text{Airy}})_i \) in the form \( (2.19) \), we get multiple terms with double infinite summation which could lead to some issues such as divergences and ambiguity of summation order. It turns out that there is no problem because each \( (H_{\text{Airy}})_i \) is given by the residue of some convergence Laurent series, hence each double infinite summation actually converges absolutely (see Lemma 2.4.15).

2. In Section 2.2.4 gauge transformations are given by \( (e'_i) \), its inverse \( (d'_i) \), and \( (s'^j) \) where \( c'_i \) is non-zero for only finitely many \( j = 1, 2, 3, \ldots \) for each fixed \( i \). In the analytic setting, we need to check that canonical coordinates transformation \( (2.28) \) follows from the canonical basis transformation \( (2.27) \). In Section 2.2.4 this is easy because there are only finitely many terms in each summation, but now we have infinite sums and getting \( (2.28) \) from \( (2.27) \) requires interchanging the orders of these infinite sums. Moreover, we also need to make sure that the summation of the type \( \sum_{i=1}^{\infty} e'_i y_i \) which appears in \( (2.28) \) will converge, as \( y_i \) may be non-zero for an infinitely many \( i = 1, 2, 3, \ldots \). We will see that if \( (e'_i), (d'_i) \) and \( (s'^j) \) are further restricted to those satisfying Condition 2.4.17 then all of these concerns will be taken care of. In particular, expressing \( (H_{\text{Airy}})_i \) in the transformed canonical coordinates will give us exactly the same gauge transformation of \( A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}} \) as given in Section 2.2.4 (see Proposition 2.4.20).

3. We discussed in Section 2.2 that \( (H_{\text{Airy}})_k \{ x^i \} \{ y_i := \partial S_0 / \partial x' \} = 0 \) where \( S_0 \in \prod_{n=1}^{\infty} \text{Sym}_n(V_{\text{Airy}}) \) is the genus zero output of the ATR using \( (V_{\text{Airy}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}) \). Even though \( S_0 \) was introduced as a formal series, we will see in Proposition 2.4.21 that it can be interpreted analytically and that its derivatives are relevant to the solution of analytic residue constraints.

For the remainder of this section, we present the technical detail leading to each point above. It is possible to skip these detail without losing any continuity to Section 2.4.3 where we will resume to discuss the embedding map \( \Phi_{t_0} : \text{Disc}^r e^M_{t_0} \to W^r_{t_0} \).
we note that (\(V\)) are double infinite summations. To check that each double infinite summation in \((H_{Airy})\) converges absolutely we note that \((H_{Airy})_{2n} = -y_{2n}\) and

\[
(H_{Airy})_{2n-1}(w) = \frac{1}{4\pi i} \oint_{|z| = \epsilon} \left( z - \sum_{k=1}^{\infty} \frac{(y_{k}e^{k}(z) + x_{k}^{f}(z))}{2zd\zeta} \right)^{2} z^{n-2}d(z^{2})
\]

(2.45)

where \(\sum_{k=1}^{\infty} (y_{k}e^{k}(z) + x_{k}^{f}(z))\) converges absolutely uniformly for \(\epsilon < |z| < M\). Adding or multiplying convergence Laurent series a finite number of times will produce another convergence Laurent series. We can expand (2.45) and examine each term more closely. For example

\[
\frac{1}{2\pi i} \oint_{|z| = \epsilon} \left( -\frac{1}{4i} \frac{1}{z^{2}} f_{i}(z) \sum_{j=1}^{\infty} x_{j}^{f}(z) \sum_{k=1}^{\infty} \frac{y_{k}e^{k}(z)}{} \right) \delta_{i,odd}
\]

(2.46)

where we have used Remark 2.3.1 to identify the residue with \((b_{Airy})_{ij}\). Note that \(\sum_{j=1}^{\infty} (x_{j})^{f}_{i} y_{k}e^{k}(z)\) converges absolutely uniformly for \(\epsilon < |z| < M\) as it is the product of \(\sum_{j=1}^{\infty} x_{j}^{f}(z)\) and \(\sum_{k=1}^{\infty} y_{k}e^{k}(z)\). Therefore, term-by-term integration is allowed and \(\sum_{j,k=1}^{\infty} (b_{Airy})_{ij} x_{j}^{f} y_{k}e^{k}(z)\) converges absolutely. Similarly, the sum \(\sum_{j,k=1}^{\infty} (a_{Airy})_{ij} x_{j}^{f} e^{k}(z)\) and \(\sum_{j,k=1}^{\infty} (c_{Airy})_{ij} x_{j}^{f} y_{k}e^{k}(z)\) also converge absolutely.

**Remark 2.4.16** Note that \(-\sum_{i=1}^{\infty} \frac{\delta_{i,odd}}{4z} f_{i}(z) e^{i}(z) = \frac{1}{4z(z^{2}-e^{i}(z))} \frac{dz_{1}}{dz}\). It follows that

\[
\sum_{i,j,k=1}^{\infty} (b_{Airy})_{ij} x_{j}^{f} y_{k}e^{k}(z) = \left( \frac{1}{2\pi i} \oint_{|z| = \epsilon} \frac{\sum_{j=1}^{\infty} x_{j}^{f}(z) \sum_{k=1}^{\infty} \frac{y_{k}e^{k}(z)}{4z(z^{2}-e^{i}(z))}}{dz} \right) dz_{1} \in V_{Airy}^{*}.
\]

Similarly, we have \(\sum_{i,j,k=1}^{\infty} (a_{Airy})_{ij} x_{j}^{f} e^{k}(z) = \frac{dz_{1}}{dz_{2}}\) and \(\omega_{0,1}(z) = ydz\).

We can recognise \(K(z_{1},z)\) to be the recursive kernel in the topological recursion of an Airy curve \(y^{2} = x\) with \(\omega_{0,2}(z_{1},z_{2})\). Consider the change of a canonical basis \(\{e^{k1,2,3,...},f_{k}=1,2,3,...\}\) of \(W_{Airy}^{M}\) where

\[
\bar{e}_{i} := \sum_{j=1}^{\infty} d_{j}^{i} (e^{j} + \sum_{k=1}^{\infty} s^{jk} f_{k}), \quad \bar{f}_{i} := \sum_{j=1}^{\infty} c_{j}^{i} f_{j},
\]

(2.47)

where \((c_{j}^{i}), (d_{j}^{i})\) and \((s^{ij})\) are tensors satisfying the following conditions:

**Condition 2.4.17**

1. \((c_{j}^{i}), (d_{j}^{i})\) are inverse of each other: \(\sum_{k=0}^{\infty} c_{k}^{i} d_{k}^{i} = \delta_{i}^{i}\) and \(\sum_{k=0}^{\infty} d_{k}^{i} c_{k}^{i} = \delta_{i}^{i}\).

2. \(\sum_{j=1}^{\infty} c_{j}^{i} f_{j} = \sum_{j=1}^{\infty} j c_{j}^{i} z^{j} d\zeta \in T_{0}L_{Airy}^{M}\) and \(\sum_{j=1}^{\infty} d_{j}^{i} f_{j} = \sum_{j=1}^{\infty} j d_{j}^{i} z^{j} d\zeta \in T_{0}L_{Airy}^{M}\).

3. There exists \(I \in Z_{>0}\) such that for all \(j = 1,2,3,...\) we have \(c_{j}^{i} = d_{j}^{i} = \delta_{i}^{i}\) for all \(i > I\).

4. \(s^{ij}\) is symmetric and \(\sum_{i,j=1}^{\infty} s^{ij} f_{i}(z_{1}) f_{j}(z_{2}) = \sum_{i,j=1}^{\infty} ij s^{ij} z_{1}^{i} z_{2}^{j} d\zeta_{1} d\zeta_{2}\) is a power series in two variables \(z_{1},z_{2}\) converges for \(|z_{1}|,|z_{2}| < M\) for some \(M > M\) (hence a holomorphic symmetric bi-differential).

**Remark 2.4.18** Compare the conditions on \((c_{j}^{i}), (d_{j}^{i})\) and \((s^{ij})\) defined here with those in Section 2.2.4 especially in Remark 2.2.28. We find that the analytic version of gauge transformation is more restrictive. This is because \(V_{Airy}^{*}\) is a larger space than \(V_{Airy}\), so loosely speaking there are more ways for things to go wrong. In
other words, any analytic gauge transformation will be a gauge transformation as considered in Section 2.2.4 but not the other way around.

Note that, we do not need to specify \( \sum_{j=1}^{\infty} d_j^i e^i \in W_{\text{Airy}}^r \) and \( \sum_{j=1}^{\infty} c_j^i e^i \in W_{\text{Airy}}^r \) as another condition, because (2.4.17.3) ensures this. If one of \((c_j^i)\) or \((d_j^i)\) satisfies (2.4.17.2) or (2.4.17.3) then so will the other one because they are the inverse of each other. This can be seen using the formula for the inverse of block matrices.

**Lemma 2.4.19** Suppose that \((c_j^i), (d_j^i)\) and \((s^j)\) satisfy the Condition (2.4.17) then we have the following

1. Let \( \sum_{j=1}^{\infty} x^j f_k \in T_0 L_M^r \) and \( \sum_{k=1}^{\infty} y_k e^k \in V_{\text{Airy}}^r \) then \( \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i d_j^i \right) e^i, \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i c_j^i \right) e^i \in V_{\text{Airy}}^r \) and \( \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} x^j f_j \right) f_j \in T_0 L_M^r \) converges absolutely uniformly.

2. Let \( \sum_{k=1}^{\infty} y_k e^k \in V_{\text{Airy}}^r \) and Let \((v^j)\) be an arbitrary vector such that \( \sum_{j=1}^{\infty} y_j v_j \) converges then \( \sum_{j=1}^{\infty} y_j \left( \sum_{i=1}^{\infty} d_j^i v^i \right) = \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i d_j^i \right) v^i \) and \( \sum_{j=1}^{\infty} y_j \left( \sum_{i=1}^{\infty} c_j^i v^i \right) = \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i c_j^i \right) v^i \).

3. Let \( \sum_{k=1}^{\infty} u_k e^k \in V_{\text{Airy}}^r \) and \( \sum_{k=1}^{\infty} v_k e^k \in V_{\text{Airy}}^r \) then \( \sum_{i,j=1}^{\infty} s^{ij} u_i v_j \) converges absolutely.

4. Let \( \sum_{k=1}^{\infty} y_k e^k \in V_{\text{Airy}}^r \) then \( \sum_{j=1}^{\infty} y_j \left( \sum_{i=1}^{\infty} s^{ij} f_j \right) = \sum_{j=1}^{\infty} y_j \left( \sum_{i=1}^{\infty} s^{ij} f_j \right) f_j \in T_0 L_M^r \) converges absolutely uniformly.

**Proof:**

1. Using (2.4.17.2), we have that \( \sum_{i=1}^{\infty} y_i d_j^i = \frac{1}{2\pi i} \oint_{|z|=\epsilon} \left( \sum_{j=1}^{\infty} \frac{y_j}{d_j^i} f_j(z) \right) \) because of the uniform convergences of each series in the integral. Therefore \( \sum_{i=1}^{\infty} y_i d_j^i \) converges for all \( j = 1, 2, 3, \ldots \) By (2.4.17.3), there exists \( J \) such that \( d_j^i = \delta_j^i \) for all \( j > J \), therefore \( \sum_{j=1}^{\infty} \sum_{i=1}^{\infty} y_i d_j^i e^j = \sum_{j=1}^{\infty} \sum_{i=1}^{\infty} y_i d_j^i e^j + \sum_{j=1}^{\infty} y_j e^j \in V_{\text{Airy}}^r \). The remaining claims follow similarly.

2. This is a straightforward consequence of (2.4.17.3):

\[
\sum_{i=1}^{\infty} y_i \left( \sum_{j=1}^{\infty} d_j^i v^i \right) = \sum_{i=1}^{\infty} y_i \left( \sum_{j=1}^{\infty} d_j^i v^i \right) + \sum_{i=1}^{\infty} y_i \left( \sum_{j=1}^{\infty} \delta_j^i v^i \right) = \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i d_j^i \right) v^i + \sum_{i=1}^{\infty} y_i v^i
\]

3. Similarly, \( \sum_{i=1}^{\infty} y_i \left( \sum_{j=1}^{\infty} c_j^i v^i \right) = \sum_{j=1}^{\infty} \left( \sum_{i=1}^{\infty} y_i c_j^i \right) v^i \).

4. Note that

\[
\sum_{i,j=1}^{\infty} s^{ij} u_i v_j = \left( \frac{1}{2\pi i} \right)^2 \oint_{|z_1|=\epsilon} \oint_{|z_2|=\epsilon} \left( \sum_{k=1}^{\infty} \frac{u_k}{k_1 z_1^2} \right) \left( \sum_{j=1}^{\infty} s^{ij} f_j(z_1) f_j(z_2) \right) \left( \sum_{k=2}^{\infty} \frac{v_k}{k_2 z_2^2} \right) .
\]

To obtain the first equality, we have used the fact that each series in the integral converges uniformly for \( \epsilon < |z_1|, |z_2| < M \) (see (2.4.17.4) for some \( \epsilon < \epsilon \) and \( M > M \). By symmetry, the second equality follows.

4. The proof is mostly identical to the part 3.
we have $\sum_{k=1}^{\infty}(\bar{y}_k e^k + x^k f_k)$ converges absolutely uniformly to $w$. Let $(H_{Airy})_i := \sum_{j=1}^{\infty} c_i^j (H_{Airy})_j$, then

$$(\bar{H}_{Airy})_i = -\bar{y}_i + \sum_{j,k=1}^{\infty} (\bar{a}_{Airy})_{ijk} x^j y^k + 2 \sum_{j,k=1}^{\infty} (\bar{b}_{Airy})_{ijk} x^j y^k + \sum_{j,k=1}^{\infty} (\bar{c}_{Airy})_{ijk} x^j y^k,$$

where $\bar{A}_{Airy} = ((\bar{a}_{Airy})_{ijk}), \bar{B}_{Airy} = ((\bar{b}_{Airy})_{ijk}), \bar{C}_{Airy} = ((\bar{c}_{Airy})_{ijk})$ are given by the gauge transformation of $A_{Airy}, B_{Airy}, C_{Airy}$ according to (2.30) to (2.32).

**Proof:** Substitute $e^i = \sum_{j=1}^{\infty} (\bar{c}_j^i e^j - \sum_{k=1}^{\infty} f_k j^2 d^s h^k)$ and $f_i = \sum_{j=1}^{\infty} d_i^j j^2$ into $\sum_{k=1}^{\infty} (y_k e^k + x^k f_k)$. Then using Lemma 2.4.19 (to help interchange infinite summations when needed and look at coefficients of $e^{i=1,2,3}$, $f_i=1,2,3,\ldots$, we have (2.48). The fact that $\sum_{k=1}^{\infty} (y_k e^k + x^k f_k)$ converges absolutely uniformly follows from part 1 and part 4 of Lemma 2.4.19.

Substitute the inverse of (2.48): $x^j = \sum_{j=1}^{\infty} (c_j^i e^j + \sum_{k=1}^{\infty} j^2 d^s h^k)$ and $y_i = \sum_{j=1}^{\infty} d_i^j j^2$ into $(H_{Airy})_i$. Using Lemma 2.4.19 we find that $(H_{Airy})_{2n} = \sum_{j=1}^{\infty} d_{2n}^j j^2$ and

$$(H_{Airy})_{2n} = 1 \frac{1}{4\pi i} \int_{|z|=\epsilon} \left( z - \sum_{k=1}^{\infty} (y_k e^k(z) + x^k f_k(z)) \right)^{2} z^{2n-2} d\left(\frac{z^2}{2}\right).$$

From (2.4.17), $\sum_{j=1}^{\infty} c_j d_j j^2 d^s h^k = \sum_{n=1}^{\infty} c_{2n} d_{2n} j^2 d^s h^k$ converges absolutely uniformly for $|z| < M$ for some $M > M$. Therefore, we can compute the summation in $(H_{Airy})_i = \sum_{j=1}^{\infty} c_j^i (H_{Airy})_j$ with the integral $f_{|z|=\epsilon}$. Expand $(H_{Airy})_i$ into the standard form, the proposition is proven.

Let $V_{Airy}$ be the vector space containing all $\sum_{k=1}^{\infty} y_k e^k \in W_{Airy}^M$, such that $\sum_{k=1}^{\infty} y_k e^k \in V_{Airy}$, where $\bar{y}_i = \sum_{j=1}^{\infty} c_j^i j^2$. Equivalently by Lemma 2.4.19 we have that $\sum_{k=1}^{\infty} y_k e^k \in V_{Airy}$ if and only if $\sum_{k=1}^{\infty} y_k e^k \in \sum_{j=1}^{\infty} c_j^i j^2$. It follows from Proposition 2.4.20 that $W_{Airy}^M = V_{Airy} \oplus T_{\theta} L_{Airy}^M$. In particular, $V_{Airy}$ is the new Lagrangian complement of $T_{\theta} L_{Airy}^M$ corresponding to the new canonical basis $\{e^{i=1,2,3}, f_i=1,2,3,\ldots\}$ of $W_{Airy}^M$.

Finally, let us compare the formal solution $L_{Airy} \subset W_{Airy}$ of $(H_{Airy})_{i=1,2,3,\ldots} = 0$ with the analytic solution $L_{Airy}^M \subset W_{Airy}^M$. In particular, we would like to understand how to interpret the generating function $S_0$ of $L_{Airy}$ analytically. The following proposition is written for the residue constraints Airy structure $(\{H_{Airy}\}_{i=1,2,3,\ldots})$ to simplify the notations but its statement and the proof presented are equally valid for any of its gauge transformations $(\{H_{Airy}\}_{i=1,2,3,\ldots})$ due to Proposition 2.4.20.

**Proposition 2.4.21** Suppose that we have a set of functions $\{y_i=1,2,3,\ldots : T_{\theta} L_{Airy}^M \to \mathbb{C}\}$ such that

$$\sum_{k=1}^{\infty} y_k(\{x^{i=1,2,3,\ldots}\}) e^k \in V_{Airy}^M, \quad (H_{Airy})_k(\{x^{i=1,2,3,\ldots}\}, \{y_i=1,2,3,\ldots\}) = 0.$$

Suppose further that $\sum_{k=1}^{\infty} y_i(x,\ldots, x^K) e^k(z), \{y_i(x,\ldots, x^K) := y_i(\{x^1,\ldots, x^K, x^{K+1} = 0\}\}$, is holomorphic in $K+1$ variables $\{x^1,\ldots, x^K, z^{-1}\}$ on some small open neighbourhoods of $\{x^1,\ldots, x^K\} = (0,\ldots, 0)$ and $|z| > \epsilon$, for any $K \in \mathbb{Z}_{\geq 0}$. Let $S_0 = \sum_{n=1}^{\infty} S_0 n \in \prod_{n=1}^{\infty} \mathrm{Sym}_n(V_{Airy})$ be the formal power series we obtained from the $g = 0$ part of the ATR of the quantum Airy structure $(V_{Airy}, A_{Airy}, B_{Airy}, C_{Airy}, \epsilon_{Airy})$. Then the functions $(\partial_i S_0)|_{x^{i}\to K, x=0}, i=1,2,3,\ldots$ and $S_0 = S_0(\{x^1,\ldots, x^K\}) := S_0(\{x^1,\ldots, x^K, x^{K+1} = 0\})$ are holomorphic on some small open neighbourhoods of $\{x^1,\ldots, x^K\} = (0,\ldots, 0)$, for any $K \in \mathbb{Z}_{\geq 0}$. In particular, we have $\partial_i S_0|_{x^{i}\to K, x=0} = y_i, i=1,2,3,\ldots$.

**Proof:** We express $y_i$ as a power series:

$$y_i(x^1,\ldots, x^K) = \sum_{n=0}^{\infty} y_i^{(n)}(x^1,\ldots, x^K), \quad y_i^{(n)}(x^1,\ldots, x^K) = \sum_{i_1,\ldots, i_n=1}^{K} \frac{1}{n!} y_{i_1,\ldots, i_n} x^{i_1} \cdots x^{i_n}.$$

By assumption, $\sum_{k=1}^{\infty} y_i(x,\ldots, x^K) e^k(z) \in V_{Airy}$ is a power series in $\{x^1,\ldots, x^K, z^{-1}\}$ which converges absolutely uniformly for $|z|^{i=1,\ldots, K} \leq r_K$ for some $r_K > 0$ and $|z| > \epsilon$, hence we are allowed to arbitrarily rearrange its terms. According to (2.45), the left-hand-side of

$$(H_{Airy})_i(\{x^1,\ldots, x^K, x^{K+1} = 0\}, \{y_j=1,2,3,\ldots\}) = 0.$$
is a residue of a simple expression involving \( \sum_{k=1}^{\infty} y_k(x^1, \ldots, x^K) e^k \), hence we can also freely rearrange its terms. Therefore, we can solve for \( y_1 \) from (2.49) by substituting in its power series expression and collecting like terms exactly as we have done in Theorem 2.2.24 for \( g_0 = 0 \), even though formal power series has been replaced by an absolutely convergent power series. The Equation (2.49) must hold for all \(|x^i=1, \ldots, K| < r_K\), so the coefficient of each monomial \( x^i \cdots x^K \), \( i_k = 1, \ldots K \) must vanish independently. In particular, we have \( y_1^{(00)} = (H_{Airy})_1^{(00)}(0,0) = (\partial x_0, \partial y_0, 1) |_{x^i=0, K} = (0,0,0) \). Therefore, \( \sum_{k=0}^{\infty} (\partial x_0, \partial y_0, 1) |_{x^i=0, K} = \sum_{n=0}^{\infty} |(\partial x_0, \partial y_0, 1) |_{x^i=0, K} = \sum_{n=0}^{\infty} y_1^{(n)} = y_1 \), is a holomorphic function in \( x^i, \ldots, x^K \) for all \( i = 1, 2, 3, \ldots \). Furthermore, for \( i = 1, \ldots, K \) we have \( \partial x_0 = (\partial x_0) |_{x^i=0, K} \) are holomorphic for \( i = 1, \ldots, K \), we conclude that the function \( S_0 \) is holomorphic for all \( (x^1, \ldots, x^K) \) such that \(|x^i=1, \ldots, K| < r_K\). \( \square \)

2.4.3 The embedding of \( Discs_{t_0}^{\epsilon} \) into \( W_{t_0}^{\epsilon} \)

In this section, the procedure we performed in Section 2.1.3 with be repeated with the covariantly constant weak symplectic flat vector bundle \((W_{\epsilon}^{\epsilon} \rightarrow Discs_{t_0}^{\epsilon}, \Omega, \nabla)\) instead of \((H \rightarrow B_{\Sigma_0}, \Omega_{\epsilon}, \nabla_{GM})\). Following [25 Section 6.1], we will define

\[
\phi \in \Gamma(Discs_{t_0}^{\epsilon}, Hom(TDiscs_{t_0}^{\epsilon}, W_{t_0}^{\epsilon})),
\]

and use it to construct the map \( \Phi_{t_0} : Discs_{t_0}^{\epsilon} \rightarrow W_{t_0}^{\epsilon} \) embedding the ‘neighbourhood’ \( Discs_{t_0}^{\epsilon} \) of \( t_0 \in Discs_{t_0}^{\epsilon} \) into the fiber \( W_{t_0}^{\epsilon} \). Finally, we show that the image of the embedding satisfies the analytic residue constraints. In other words, \( \text{im}\Phi_{t_0} \) is contained inside \( L_{Airy}^{\epsilon} \subset W_{t_0}^{\epsilon} \cong W_{Airy}^{\epsilon} \) (see Proposition 2.4.24).

Let us fix the reference point \( t_0 := (x = z^2, y = z) \in Discs_{t_0}^{\epsilon} \) and define the subspace \( Discs_{t_0}^{\epsilon} \subset Discs_{t_0}^{\epsilon} \) containing \( t_0 \) given by

\[
Discs_{t_0}^{\epsilon} := \left\{ t = (x = a(t) + z^2, y = \sum_{k=0}^{\infty} b_k(t)z^k) \in Discs_{t_0}^{\epsilon} \mid \sum_{k=0}^{\infty} b_k(t)z^k \text{ converges for } \left| z \right| < M \text{ for some } M > M \text{ and min}(M^2 - M, \epsilon^2) > |a(t) - a(t_0)| \right\}.
\]

Conceptually, we think of \( Discs_{t_0}^{\epsilon} \) as a small neighbourhood of \( t_0 \) inside \( Discs_{t_0}^{\epsilon} \) (although, it is not a neighbourhood according to the topology given in Remark 2.4.7). Similar to before, for any \( t \in Discs_{t_0}^{\epsilon} \), the kinematic tangent space \( T_t Discs_{t_0}^{\epsilon} \) is defined to be the set of \( v \in Discs_{t_0}^{\epsilon} \) such that \( \gamma(t) := t + tv \) defines a path \( \gamma : (-\delta, \delta) \rightarrow Discs_{t_0}^{\epsilon} \) for some \( \delta > 0 \). In other words,

\[
T_t Discs_{t_0}^{\epsilon} := \left\{ v = A \frac{\partial}{\partial a} + \sum_{k=0}^{\infty} b_k \frac{\partial}{\partial b_k} \in T_t Discs_{t_0}^{\epsilon} \mid \sum_{k=0}^{\infty} b_k z^k \text{ converges for } \left| z \right| < M \text{ for some } M > M \text{ and min}(M^2 - M, \epsilon^2) > |a(t) - a(t_0)| \right\}.
\]

Remark 2.4.22 We will let the definition of \( \Gamma(Discs_{t_0}^{\epsilon}, W_{\epsilon}^{\epsilon}), \Gamma(Discs_{t_0}^{\epsilon}, TDiscs_{t_0}^{\epsilon}) \) and \( \Gamma(Discs_{t_0}^{\epsilon}, Hom(TDiscs_{t_0}^{\epsilon}, W_{\epsilon}^{\epsilon})) \) to be exactly as given in Remark 2.4.8 with \( Discs_{t_0}^{\epsilon} \) replaced by \( Discs_{t_0}^{\epsilon} \).

At any point \( t \in Discs_{t_0}^{\epsilon} \), the map \( \phi_t \) arises from the consideration of the infinitesimal deformations within the moduli space \( Discs_{t_0}^{\epsilon} \) of the disc \( D_{t,M} \rightarrow C^2 \) embedded inside the foliated symplectic surface \( (C^2, \Omega_{C^2} := dx \wedge dy, \{x = const\}) \). It is given by the following diagram:

\[
T_t Discs_{t_0}^{\epsilon} \xrightarrow{\phi_t} \lim_{M(t) \searrow M} \Gamma(D_{t,M}, TC^2|_{D_{t,M}} \rightarrow TD_{t,M}) \xrightarrow{\phi_t} \lim_{M(t) \searrow M} \Gamma(D_{t,M}, \Omega^1_{D_{t,M}}) \rightarrow W_{t(\epsilon,M)}^{(\epsilon, M)} \subset W_{t(\epsilon)}^{\epsilon,M}.
\]

Where \( M(t) \) and \( \epsilon(t) \) are given as follows

\[
\epsilon(t) := \sqrt{\epsilon^2 - |a(t) - a(t_0)|} \leq \epsilon < M \leq M(t) := \sqrt{M^2 + |a(t) - a(t_0)|}.
\]

Note that for all \( t \in Discs_{t_0}^{\epsilon} \), \( \sum_{k=0}^{\infty} b_k(t)z^k \) converges for \( \left| z \right| < M \) for some \( M \) where \( \bar{M} > M(t) > M \). The isomorphism \( T_t Discs_{t_0}^{\epsilon} \xrightarrow{\sim} \lim_{M(t) \searrow M} \Gamma(D_{t,M}, TC^2|_{D_{t,M}} \rightarrow TD_{t,M}) \) follows because a tangent vector \( v \in \)
\(T_1 Discs^{t, M}_t\) gives an infinitesimal deformation of \(\mathbb{D}_{t, M}, M > M(t)\) which can be thought of as a global section \(n_v\) of the normal bundle \(\nu_{t, M}/\nu \cong TC^2|_{\bar{\nu}_{t, M}}/T\mathbb{D}_{t, M}\). The map \(\Gamma(\mathbb{D}_{t, M}, TC^2|_{\bar{\nu}_{t, M}}/T\mathbb{D}_{t, M}) \xrightarrow{\sim} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M})\) is given by \(n_v \mapsto \Omega_{c2}(n_v, \cdot)|_{\bar{\nu}_{t, M}}\). It is an isomorphism because \(\Omega_{c2}\) is non-degenerate by definition and \(\mathbb{D}_{t, M} \subset C^2\) is obviously a Lagrangian submanifold. This induces the isomorphism of the direct limit

\[
\lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, TC^2|_{\bar{\nu}_{t, M}}/T\mathbb{D}_{t, M}) \xrightarrow{\sim} \lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M}).
\]

Using the standard local coordinates \(z\) on \(\mathbb{D}_{t, M}\), we find that

\[
\lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M}) \cong \left\{ \xi \in \mathbb{C}[z] \left| \frac{dz}{z} \text{ converges for } |z| < M \text{ for some } M > M(t) \right\} \mapsto W^{\epsilon, M}(t) \subset W^{\epsilon, M}_t.
\]

**Remark 2.4.23** Observe that, \(\lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M})\) is embedded as a Lagrangian subspace of \(W^{\epsilon, M}(t)_t\), i.e. it is a maximal subspace of \(W^{\epsilon, M}(t)_t\) such that if \(\xi_1, \xi_2 \in \lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M})\) then \(\Omega_{Airy}(\xi_1, \xi_2) = 0\). In other words, \(\phi_t\) embeds \(T_1 Discs^{t, M}_t\) as a Lagrangian subspace of \(W^{\epsilon, M}_t\). On the other hand, it is not always true that \(\phi_t\) embeds \(T_1 Discs^{t, M}_t\) as a Lagrangian subspace of \(W^{\epsilon, M}_t\), in fact \(\lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M}) \subset T_0 L^{M}_{Airy}\) with an equality if and only if \(a(t) = a(t_0)\).

Let us write down \(\phi_t\) explicitly. Consider a tangent vector

\[
v = A \frac{\partial}{\partial a} + \sum_{k=0}^{\infty} B_k \frac{\partial}{\partial b_k} \in T_1 Discs^{t, M}_t
\]

where \(\sum_{k=0}^{\infty} B_k z^k\) converges absolutely for \(|z| < M\) for some \(M > M(t)\). The vector \(v\) maps to

\[
n_v = A \frac{\partial}{\partial a} + \sum_{k=0}^{\infty} B_k \frac{\partial}{\partial b_k}\phi_t = A \phi_t + \sum_{k=0}^{\infty} B_k z^k \phi_t \in \lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, TS|_{\nu_{t, M}}/T\mathbb{D}_{t, M}).
\]

Therefore, the value of \(\phi_t\) on \(v\) is given by

\[
\phi_t(v) = \Omega_{t}(n_v, \cdot)|_{\mathbb{D}_{t, M}} = \left(A dy - \sum_{k=0}^{\infty} B_k z^k dx\right)_{\mathbb{D}_{t, M}} = \left(A \sum_{k=1}^{\infty} k b_k z^{k-1} - 2 \sum_{k=0}^{\infty} B_k z^{k+1}\right) dz \in \lim_{M > M(t)} \Gamma(\mathbb{D}_{t, M}, \Omega^1_{t, M}) \mapsto W^{\epsilon, M}(t)_t \subset W^{\epsilon, M}_t.
\]

In other words,

\[
\phi_t = \left(\sum_{k=1}^{\infty} k b_k z^{k-1} dz\right) - 2 \sum_{k=0}^{\infty} (z^{k+1} dz) db_k,
\]

and it is easy to check that \(d\phi_t = 0\).

Let us now construct the map \(\Phi_{t_0}: Discs^{t, M}_t \hookrightarrow W^{t, M}_t\) embedding the neighbourhood \(Discs^{t, M}_t\) of \(t_0 = (x = z^2, y = z) \in Discs^{t, M}_t\) into the fiber \(W^{t, M}_0\) in the same way we did in Section 2.1.3. We send the zero vector \(0_t \in W^{t, M}_t\) at any point \(t_1 \in Discs^{t, M}_t\) into \(W^{t, M}_{t_1}\) at \(t_0\) via parallel transport using the connection \(\nabla + \phi\). Where \((\nabla + \phi)\xi := \nabla \xi + \phi\) for \(\xi \in \Gamma(Discs^{t, M}_t, W^{t, M}_t)\). Since \(d\phi_0 = 0\), there exists a section \(\theta \in \Gamma(Discs^{t, M}_t, W^{t, M}_t)\) such that \(d\phi t = \phi\). We can write down \(\theta_t\) explicitly for any \(t = (x = z^2 + a(t), y = y) \in Discs^{t, M}_t\):

\[
\theta_t = -y dx = - \sum_{k=0}^{\infty} b_k(t) z^k d(z^2) = -2 \sum_{k=0}^{\infty} b_k(t) z^{k+1} dz.
\]

In general, given \(t \in Discs^{t, M}_t\), the parallel transport using \(\nabla + \phi\) of \(0_t \in W^{t, M}_t\) from \(t_1 \in Discs^{t, M}_t\) to \(W^{t, M}_t\) at \(t\) is path-independent and it is given by

\[
v_t(t) = -\theta_t + \exp((a(t) - a(t_1))L_{\bar{\nu}_{t_0}}) o_t.
\]
We note that $v_t(t)$ is well-defined for all $t_1 \in Discs_{t_0}^{s,t}$ because $|a(t) - a(t_1)| < \min(M^2 - M^2, \epsilon^2)$ by definition, hence $\exp((a(t) - a(t_1))\mathcal{L}_{\frac{x}{\partial x}})\theta_{t_1} \in W_{t_0}^{r,t}$. It follows that

$$\Phi_{t_0}(t) := v_t(t_0) = -\theta_{t_0} + \exp((a(t_0) - a(t))\mathcal{L}_{\frac{x}{\partial x}})\theta_{t} \in W_{t_0}^{r,t},$$

for all $t \in Discs_{t_0}^{s,t}$.

**Proposition 2.4.24** (Section 6.3) Let $t_0 = (x = z^2, y = z) \in Discs_{t_0}^{s,t}$. The image of the map $\Phi_{t_0} : Discs_{t_0}^{s,t} \rightarrow W_{t_0}^{r,t}$ satisfies the residue constraints (2.34), i.e. $\text{im}\Phi_{t_0} \subseteq \Omega^{M}_{Airy} \subset W_{t_0}^{r,t} \cong W_{Airy}^{r,t}$.

**Proof:** At the point $t = (x = z^2 + a(t), y = \sum_{k=0}^{\infty} b_k(t) z^k) \in Discs_{t_0}^{s,t}$, we have

$$\Phi_{t_0}(t) = zd(z^2) - \exp((a(t_0) - a(t))\mathcal{L}_{\frac{x}{\partial x}})(yd(z^2)).$$

We will show that $\Phi_{t_0}(t) \in W_{t_0}^{r,t}$ satisfies the residue constraints. In fact, for any $m, n \in \mathbb{Z}_{\geq 0}$ we have

$$\text{Res}_{z=0} \left( \left( z - \frac{\Phi_{t_0}(t)}{2zd} \right)^m \frac{z^{2n}d(z^2)}{zd(z^2)} \right) = \text{Res}_{z=0} \left( \left( \frac{\exp(-a(t)\mathcal{L}_{\frac{x}{\partial x}})(y)dz^2}{zd(z^2)} \right)^m \frac{z^{2n}dz}{zd(z^2)} \right)$$

$$= \text{Res}_{z=0} \left( \frac{\exp(-a(t)\mathcal{L}_{\frac{x}{\partial x}})(y(z^2))}{zd(z^2)} \right)^m = 0.$$

We justify the vanishing of the residue as follows. Since $t \in Discs_{t_0}^{s,t}$ and $a(t_0) = 0$, we have that $|a(t)| < \epsilon^2$ and $y^m(z^2 + a(t))z^2 d(z^2)$ is holomorphic for $|z| < \sqrt{M^2 + |a(t)|}$. In particular it contains no $\frac{dz}{z}$ and it belongs to $W_{\Omega_{Airy}}^{r,t} \subset W_{Airy}^{r,t}$. Therefore

$$\exp(-a(t)\mathcal{L}_{\frac{x}{\partial x}})(y^m(z^2 + a(t))z^2 d(z^2)) \in W_{Airy}^{r,t}$$

by Lemma 2.4.9 which also contains no $\frac{dz}{z}$ term. In the case where $m = 1, 2$, we can see that $\Phi_{t_0}(t)$ satisfies the residue constraints for all $t \in Discs_{t_0}^{s,t}$ as claimed.

**Example 2.4.25** Let $t_0 = (x = z^2, y = z)$ and $t = (x = z^2 + a, y = z)$, then

$$\Phi_{t_0}(t) = zd(z^2) - \exp(-a\mathcal{L}_{\frac{x}{\partial x}})(zd(z^2))$$

$$= zd(z^2) - zd(z^2) + a \frac{dz}{z} + \sum_{k=2}^{\infty} \frac{a^k (2k - 3)!!}{k!} \frac{ dz}{z}$$

In $J$ coordinates we would have

$$J_{a} = a, \quad J_{2k-3} = \frac{a^k (2k - 3)!!}{k!} z^{k - 1}, \quad k > 1$$

and the rest of $J_a$ are zero. We can check that $\{J_a\}$ we have found satisfies the set of equations $\{(H_{Airy})_{1,2,3,\ldots} = 0\}$ defining $L_{Airy}^{M} \subset W_{Airy}^{r,t}$.

**Remark 2.4.26** Since $(W_{Airy}^{r,t} \rightarrow Discs_{t_0}^{s,t}, \Omega, \nabla, \phi)$ is a weak symplectic flat vector bundle with $\nabla$-covariant constant $\Omega$ and $d_{\nabla}\phi = 0$, it would be nice to be able to conclude that $\text{im}\Phi_{t_0}$ is a Lagrangian submanifold using Proposition 2.1.24 Unfortunately, Proposition 2.1.24 does not apply because $W_{Airy}^{r,t}$ has an infinite rank. However, we can show that $\text{im}\Phi_{t_0}$ is isotropic in the sense that

$$T_{\Phi_{t_0}(t)} \text{im}\Phi_{t_0} := \{v \in T_{t_0} Discs_{t_0}^{s,t} \mid \text{im}\Phi_{t_0}(t) = 0 \} \subset W_{t_0}^{r,t}$$

is an isotropic subspace where $d_{\Phi_{t_0}(t)} = \exp((a(t_0) - a(t))\mathcal{L}_{\frac{x}{\partial x}})\phi_t$. For any $v_1, v_2 \in T_{t_0} Discs_{t_0}^{s,t}$ we have by Lemma 2.4.14 and the fact that $\phi_t$ embeds $T_{t_0} Discs_{t_0}^{s,t}$ as a Lagrangian subspace of $W_{t_0}^{r,t}$ that

$$\Omega_{\phi_t}(v_1, d_{\Phi_{t_0}(t)}(v_1), v_2) = 0.$$
2.5 From Local To Global

In Section 2.1 we studied the complex analytic moduli space of \( F \)-transversal genus \( g \) curves in a foliated symplectic surface \((S, \Omega_S, F)\) and the embedding of an open neighbourhood \( B_{\Sigma_0} \) into a fiber \( H_{\Sigma_0} = H^1(\Sigma_0, \mathbb{C}) \) of \( H \to B \). All considerations were done at the level of cohomology which gives a global picture of the deformations. In Section 2.4 we studied what deformations of \( \Sigma \) look near a ramification point and the embedding of \( Discs_{\Sigma_0}^M \) into the fiber \( W_{t_0}^M \) of \( W_\ast \to Discs^M \), which is a local picture of the deformations. The idea of this section is to connect the two pictures by lifting each cohomology class in Section 2.1 to a differential form with Laurent series expansions near each ramification point given by a series introduced in Section 2.4.

First of all, since there are more than one ramification points on \( \Sigma \) in general, instead of \( W_{t_0}^M \) we will consider \( W_{t_0}^M := \prod_{\alpha \in Ram} W_{\epsilon_\alpha M_0} \), a vector bundle of differential forms locally defined on the disjoint union of some annulus on \( \Sigma \), each centered at a ramification point. We are going to introduce the vector bundle \( G \to B_{\Sigma_0} \subseteq B \) where the fibers \( G_{\Sigma} \) are given by the space of elements of \( W_{t_0}^M \) which can be extended to a holomorphic form on the entire \( \Sigma \) with some discs removed = \( \Sigma \setminus \cup_{\alpha \in Ram} \mathbb{D}_{\alpha, \epsilon_\alpha} (\Sigma) \). There is a map from \( G \to W_{t_0}^M \) given by Laurent expansion around ramification points and a map from \( G \to H \) given by taking cohomology classes. Therefore, \( G \) is an ‘intermediate’ vector bundle between \( W_{t_0}^M \) and \( H \) in this sense.

We equip \( G \) with the connection given by differentiation along a foliation leaf \( \nabla_F \). In fact, this is the unique choice of connection for \( G \), since applying \( \nabla_F \) on any element of \( G_{\Sigma} \) can create poles only at ramification points. It follows that the parallel transport on \( G \) from \( [\Sigma] \in B_{\Sigma_0} \) to \( [\Sigma'] \in B_{\Sigma_0} \) is given by pulling-back a holomorphic form on \( \Sigma \) to \( \Sigma' \) along the foliation leaves. Clearly, the pull-back will only be well-defined away from ramification points. Conceptually, a parallel transport will only be possible if \( [\Sigma'] \in B \) is sufficiently close to \( [\Sigma] \in B \) such that each ramification point \( r_\alpha (\Sigma') \) (or rather, the point on \( \Sigma \) connected to \( r_\alpha (\Sigma') \) via a foliation leaf) does not move too far from \( r_\alpha (\Sigma) \) and it remains contained inside the discs \( \mathbb{D}_{\alpha, \epsilon_\alpha} (\Sigma) \) to be removed from \( \Sigma \). This adds another reason why we need \( B_{\Sigma_0} \) to be sufficiently small, a condition first mentioned in Section 2.1 and we have delayed making it precise until this section.

Since Section 2.4 is an analytic approach to 25, Section 6], we may think of this section as an analytic approach to 25, Section 7]. We outline the content as follows. After fixing terminologies in Section 2.5.1 we discuss precisely how the open neighborhood \( B_{\Sigma_0} \subseteq B \) should be selected. Not surprisingly, the condition \( B_{\Sigma_0} \) needs to satisfy also depends on the sizes of annulus \( \{\epsilon_\alpha \in Ram\} \), \( \{M_\alpha \in Ram\} \), and the choice of \( (F, \Omega_S) \)-charts \( U_a \) around each ramification point. Then we will introduce the vector bundle \( G \) and discuss some of its properties in Section 2.5.3. Among other things, we will show that \( G \) is a coisotropic sub-bundle of \( W_{t_0}^M \). In Section 2.5.4 the residue constraints Airy structure on \( W_{t_0}^M \) will be introduced as the product of residue constraints Airy structure. Then, we will discuss the connection \( \nabla_F \) and parallel transport on \( G \) in detail in Section 2.5.5. The comparison between connection and parallel transport on \( H \to B, W_{t_0}^M \to Discs^M \), and \( G \to B_{\Sigma_0} \) will be studied in Section 2.5.6. Finally, in Section 2.5.7 we will define the embedding map \( \Phi_{\Sigma_0} : B_{\Sigma_0} \to H_{\Sigma_0} \) defined in Section 2.1.3 and \( \Phi_{t_0} : Discs_{\Sigma_0}^M \to W_{t_0}^M \) defined in Section 2.4.3 and argue that the image of \( \Phi_{\Sigma_0} \) satisfies the residue constraints. The main result of this section, Proposition 2.5.38 [25 Proposition 7.1.2] summarizes the relationship between \( \Phi_{\Sigma_0}, \Phi_{\Sigma_0} \) and \( \Phi_{t_0} \). In fact, since we are working entirely in an analytic framework, we are going to see the relationship between the Lagrangian submanifold \( L_{\Sigma_0} := \text{im} \Phi_{\Sigma_0} \subset H_{\Sigma_0} \) and \( L_{\Sigma_0, \text{Ram}} \), treated as an actual subset of \( W_{t_0}^M \).

2.5.1 Basic setup and definitions

Let us fix a reference point \( [\Sigma_0] \in B \) and a collection of \( (F, \Omega_S) \)-charts \( U_{\alpha, \epsilon} := \{ (U_{\alpha, \epsilon} \in Ram, x_\alpha \in Ram, y_\alpha \in Ram) \} \) such that each \( U_{\alpha, \epsilon} \in Ram \) contains the ramification point \( r_\alpha (\Sigma_0) \) of \( \Sigma_0 \) and \( \Sigma_0 \cap U_{\alpha, \epsilon} \) is bi-holomorphic to a simply-connected open subset of \( \mathbb{C} \) with the standard local coordinate \( z_\alpha := \sqrt{x_\alpha - x_\alpha (r_\alpha)} \). We choose \( B_{\Sigma_0} \) to be sufficiently small such that for all \( [\Sigma] \in B_{\Sigma_0}, \Sigma \cap U_a \) contains the ramification point \( r_\alpha (\Sigma) \) of \( \Sigma \) and it is bi-holomorphic to a simply-connected open subset of \( \mathbb{C} \) with the standard local coordinate \( z_\alpha := \sqrt{x_\alpha - x_\alpha (r_\alpha)} \).

For each \( [\Sigma] \in B_{\Sigma_0} \) the parameterization of \( \Sigma \cap U_{\alpha} \) takes the form

\[
t_\alpha (\Sigma) = (x_\alpha = a_\alpha (\Sigma) + z_\alpha^2, y_\alpha = b_\alpha (\Sigma) + b_1 (\Sigma) z_\alpha + b_2 (\Sigma) z_\alpha^2 + ...).
\]

Let us emphasize that coefficients \( \{a_\alpha (\Sigma), b_0 (\Sigma), b_1 (\Sigma), b_2 (\Sigma), \ldots\} \) depends on our choice of the \( (F, \Omega_S) \)-local coordinates \( \{x_\alpha, y_\alpha\} \). In particular, we often choose \( \{x_\alpha, y_\alpha\} \) such that a reference point \( [\Sigma_0] \in B \) is parameterized by \( t_\alpha (\Sigma_0) = (x_\alpha = z_\alpha^2, y_\alpha = z_\alpha) \).

Pick \( \{\epsilon_\alpha \in Ram \in \mathbb{R}\} \) and \( \{M_\alpha \in Ram \in \mathbb{R}\} \) such that \( 0 < \epsilon_\alpha < M_\alpha \) and define the following discs and annulus on

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Chapter 2. Airy Structures and Deformation of Curves

2.5.2 Choosing

\(\{\epsilon_\alpha \in \text{Ram}\}, \{M_\alpha \in \text{Ram}\}, \mathcal{U}_{\text{Ram}}\) and \(\mathcal{B}_{\Sigma_0}\)

We will now write down a precise summary of how \(\{\epsilon_\alpha \in \text{Ram}\}, \{M_\alpha \in \text{Ram}\}, \mathcal{U}_{\text{Ram}}=\{(U_\alpha \in \text{Ram}, x_\alpha \in \text{Ram}, y_\alpha \in \text{Ram}\}\}\) and \(\mathcal{B}_{\Sigma_0}\) can be selected. Once they are selected, they should remain fixed for the entire calculation. Let \([\Sigma_0] \in \mathcal{B}\) be the fixed reference point. For each \(\alpha \in \text{Ram}\), we pick \(\epsilon_\alpha, M_\alpha \in \mathbb{R}, 0 < \epsilon_\alpha < M_\alpha\), a collection of \((\mathcal{F}, \Omega)\)-charts \(\mathcal{U}_{\text{Ram}}=\{\{(U_\alpha \in \text{Ram}, x_\alpha \in \text{Ram}, y_\alpha \in \text{Ram}\}\}\) with \(r_\alpha(\Sigma_0) \in U_\alpha\) and an open neighbourhood \(\mathcal{B}_{\Sigma_0}\) of \([\Sigma_0]\) satisfying Condition 2.5.2 below.
Remark 2.5.1 These conditions are technical and can be skipped in the first reading. They are sufficient but not necessary conditions for the results of this section to hold. It is usually more practical to pick an appropriate $\U_{\text{Ram}}$ then select $\{\epsilon_{\alpha}\in \text{Ram}\}, \{M_{\alpha}\in \text{Ram}\}$ such that $\mathcal{D}_{0,M_{\alpha}}(\Sigma_{0}) \subset \Sigma \cap U_{\alpha}$ before picking $\mathcal{B}_{\Sigma_{0}}$ and directly check that it is small enough for all the needed objects, such as $\Phi : \mathcal{B}_{\Sigma_{0}} \to G_{\Sigma_{0}}$, to be defined.

Condition 2.5.2

**B**$\Sigma_{0}$ is a contractible open neighbourhood of $[\Sigma_{0}]$ which can be covered by a single coordinate chart $(\mathcal{B}_{\Sigma_{0}}, u^{1}, \ldots, u^{\theta})$.

**B**2.5.2.2 For all $[\Sigma] \in \mathcal{B}_{\Sigma_{0}}$, the open subset $\Sigma \cap U_{\alpha} \subset \Sigma$ is biholomorphic to a simply-connected open subset of $\mathbb{C}$ with the standard local coordinate $z_{\alpha} := \sqrt{x_{\alpha} - x_{\alpha}(\Sigma)}$ and $\mathcal{D}_{0,M_{\alpha}}(\Sigma) \subset \Sigma \cap U_{\alpha}$.

**B**2.5.2.3 There exists a collection of $(\mathcal{F}, \Omega_{\Sigma})$-charts $\mathcal{U}_{\alpha} = \{(U_{p}, p_{\xi}) \in \text{Ram}\}$ such that for all $[\Sigma] \in \mathcal{B}_{\Sigma_{0}}$, the parallel transport on the vector bundle $G \to \mathcal{B}_{\Sigma_{0}}$, the fiber $G_{\Sigma}$ to the fiber $G_{\Sigma}$ is possible for any holomorphic form $\xi \in \Gamma(\Sigma_{0}, \Omega_{\Sigma_{0}}) \subset G_{\Sigma_{0}}$ according to Lemma 2.5.32. Additionally, the image of $\tilde{\alpha}_{\alpha,\epsilon_{\alpha},M_{\alpha}}(\Sigma_{0})$ via the map $s_{\Sigma_{0},\Sigma}$ (see Definition 2.5.28) is contained in $\Sigma_{0} \cap U_{\alpha}$.

**B**2.5.2.4 Let $\mathcal{U}_{\alpha} = \{(U_{p}, p_{\xi}) \in \text{Ram}\}$ be the collection of $(\mathcal{F}, \Omega_{\Sigma})$-charts from (2.5.2.3). For all $[\Sigma] \in \mathcal{B}_{\Sigma_{0}}$, the parallel transport on the vector bundle $G \to \mathcal{B}_{\Sigma_{0}}$, the fiber $G_{\Sigma}$ to the fiber $G_{\Sigma}$ is possible according to Lemma 2.5.32 for any $\xi \in G_{\Sigma}$ holomorphic on $\cup_{p \in \xi_{\alpha}} \cup_{\alpha \in \text{Ram}} \mathcal{D}_{0,\epsilon_{\alpha}}(\Sigma)$. Additionally, the image of $\tilde{\alpha}_{\alpha,\epsilon_{\alpha},M_{\alpha}}(\Sigma_{0})$ via the map $s_{\Sigma_{0},\Sigma}$ is contained in $\Sigma \cap U_{\alpha}$.

Remark 2.5.3 We can summarize the basic idea behind each part in Condition 2.5.2 as follows:

**B**2.5.2.1 Simplifies our discussions by avoiding any complications arises from coordinates transformations, transition functions, and possible monodromies of parallel transport when $\mathcal{B}_{\Sigma_{0}}$ wrap around a singularity in $\mathcal{B}$.

**B**2.5.2.2 Helps us deal with neighbourhoods of ramification points of each $\Sigma \in \mathcal{B}_{\Sigma_{0}}$. In particular, this helps fix the definition of the map $\gamma : \mathcal{B}_{\Sigma_{0}} \hookrightarrow \text{DISCS}_{\text{Ram}}$, the map $i : G \hookrightarrow W_{\text{Ram}}$ (see Equation (2.54)), the discs $\mathcal{D}_{0,\epsilon_{\alpha}}(\Sigma)$, $\mathcal{D}_{0,M_{\alpha}}(\Sigma)$ and annulus $\tilde{\alpha}_{\alpha,\epsilon_{\alpha},M_{\alpha}}(\Sigma)$.

**B**2.5.2.3 Helps us define the section $\theta \in \Gamma(\mathcal{B}_{\Sigma_{0}}, G)$ which will be important in the construction of $\Phi : \mathcal{B}_{\Sigma_{0}} \to G_{\Sigma_{0}}$ embedding the neighbourhood $\mathcal{B}_{\Sigma_{0}}$ into the fiber $G_{\Sigma_{0}}$ analogous to what we did in Section 2.4 and Section 2.4.

**B**2.5.2.4 Makes sure that we are allowed to perform a parallel transport of $\theta_{\Sigma}$ necessary to define the embedding map $\Phi : \mathcal{B}_{\Sigma_{0}} \to G_{\Sigma_{0}}$.

2.5.3 The vector bundle $G \to \mathcal{B}_{\Sigma_{0}}$ and its properties

We are going to define the vector bundle $(G \to \mathcal{B}_{\Sigma_{0}}, \nabla_{\mathcal{F}})$ in this section (see Definition 2.5.22). The fiber of $G$ over any point $[\Sigma] \in \mathcal{B}_{\Sigma_{0}}$ is the infinite-dimensional vector space $G_{\Sigma}$ given by Definition 2.5.4 below. By taking a Laurent expansion in the vicinity of each ramification point $r_{\alpha} \in \text{Ram}$ we obtain a vector bundle morphism $i : G \hookrightarrow W_{\text{Ram}}$, embedding $G$ as a vector sub-bundle of $W_{\text{Ram}}$. It will follow from Proposition 2.5.18 that $G$ is, in fact, a coisotropic vector sub-bundle of $W_{\text{Ram}}$. Consider $G_{\Sigma}^{\perp} \subset G_{\Sigma}$ as a group acting on $W_{\text{Ram}}$ by vector addition, then we will see in Proposition 2.5.19 that the symplectic reduction of $(W_{\text{Ram}}^{\perp} \Omega_{\text{Airy}})$ is given by $(H_{\Sigma}, \Omega_{\Sigma})$. In particular, we have the surjective vector bundle morphism $\pi : G \to H$ given by taking the cohomology class. Together, the map $i$ and $\pi$ establish $G \to \mathcal{B}_{\Sigma_{0}}$ as an intermediate vector bundle connecting $W_{\text{Ram}} \to \text{DISCS}_{\text{Ram}}$ and $H \to \mathcal{B}$ as we will discuss further in Section 2.5.6 and Section 2.5.7.

**Definition 2.5.4** For any $[\Sigma] \in \mathcal{B}$, the infinite-dimensional vector space $G_{\Sigma}$ is given by

$$G_{\Sigma} := \left\{ \xi \in \lim_{\xi_{\alpha} \to \infty} \Gamma(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \mathcal{D}_{\alpha,\epsilon_{\alpha}}(\Sigma_{0}), \Omega_{\Sigma}^{2}) \mid \int_{\mathcal{D}_{0,\epsilon_{\alpha}}} \xi = 0, \alpha \in \text{Ram} \right\}.$$  

What we meant is that if $\xi \in G_{\Sigma}$ then $\xi$ is a holomorphic differential on some open neighbourhood of $\Sigma \setminus \cup_{\alpha \in \text{Ram}} \mathcal{D}_{\alpha,\epsilon_{\alpha}}(\Sigma)$. In particular, $\xi$ is holomorphic on some open set containing $\tilde{\alpha}_{\alpha,\epsilon_{\alpha},M_{\alpha}}(\Sigma)$.  

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Then, we will define the vector bundle $G = B$.

Definition 2.5.7 For any $\Sigma \in B$,

$$G^{\text{mer}} = \left\{ \xi \in \Gamma \left( \Sigma, \Omega^1_{\Sigma} \left( \sum_{\alpha \in \text{Ram}} nr_{\alpha} \right) \right) \mid \text{for some } n \in \mathbb{Z}_{\geq 0} \text{ and } \text{Res}_{r_n} \xi = 0, \alpha \in \text{Ram} \right\}.$$ 

In other words, $G^{\text{mer}}$ is a vector space of residueless meromorphic differential forms on $\Sigma$ with poles at ramification points.

For each $\alpha \in \text{Ram}$, the Laurent series representation of $\xi \in G_{\Sigma}$ in the standard local coordinate center at $z_{\alpha} = 0$ converges absolutely for $\varepsilon_{\alpha} < |z_{\alpha}| < M_{\alpha}$ for some $\varepsilon_{\alpha} < \varepsilon_{\alpha} < M_{\alpha} < M_{\alpha}$ and contains no $\frac{dz_{\alpha}}{z_{\alpha}}$ term because $\oint_{\partial B_{\alpha,\varepsilon_{\alpha}}} \xi = 0$. Therefore, this define the map $i_{\alpha} : G_{\Sigma} \hookrightarrow W_{t,\alpha}(\Sigma)$. Performing the Laurent expansion at every ramification point of $\Sigma$, we obtain the map

$$i := \sum_{\alpha \in \text{Ram}} [\alpha] \otimes i_{\alpha} : G_{\Sigma} \hookrightarrow W^{\text{Ram}}_{t}(\Sigma)$$

(2.54)

for any $[\Sigma] \in B_{\Sigma}$. Hence, instead of writing $i(G_{\Sigma}) \subset W^{\text{Ram}}_{t}(\Sigma)$ we will sometime write $G_{\Sigma} \subset W^{\text{Ram}}_{t}(\Sigma)$.

Remark 2.5.6 Let us emphasize that the definition of the map $i$ depends on our choice of the collection of coordinate charts $U_{\text{Ram}}$. Choosing a different $(F, \Omega_{S})$-local coordinate system $(x_{\alpha}, y_{\alpha})$ on $U_{\alpha}$ for any $\alpha \in \text{Ram}$ will result in a different map $i$ and hence, a different embedding $G_{\Sigma} \hookrightarrow W^{\text{Ram}}_{t}(\Sigma)$.

We can apply the symplectic form $\Omega_{\text{Airy}}$ on vectors in $G_{\Sigma}$. In fact, using Riemann-bilinear identity we can obtain a nice alternative expression. For $\xi_1, \xi_2 \in G_{\Sigma}$ we have

$$\Omega_{\text{Airy}}(i(\xi_1), i(\xi_2)) = \sum_{\alpha \in \text{Ram}} \text{Res}_{z_{\alpha}} = 0 \left( i_{\alpha}(\xi_1) \int i_{\alpha}(\xi_2) \right) = \frac{1}{2\pi i} \sum_{\alpha \in \text{Ram}} \oint_{\partial B_{\alpha,\varepsilon_{\alpha}}} \left( \xi_1 \int \xi_2 \right)
= \frac{1}{2\pi i} \sum_{k=1}^{g} \left( \oint_{A_k} \xi_2 \oint_{B_k} \xi_1 - \oint_{B_k} \xi_2 \oint_{A_k} \xi_1 \right).$$

(2.55)

For each $[\Sigma] \in B_{\Sigma}$, we are going to show that $G_{\Sigma} \subset W^{\text{Ram}}_{t}(\Sigma)$ is a coisotropic subspace and that $G_{\Sigma}/G^{\Sigma}_{\text{mer}} \cong \mathcal{H}_{\Sigma}$. Then, we will define the vector bundle $G \to B$. But first, we need some preliminary definitions and results.

Definition 2.5.7 For any $[\Sigma] \in B$, the infinite-dimensional vector space $V_{\Sigma}$ is given by

$$V_{\Sigma} := \left\{ \xi \in G_{\Sigma} \mid \oint_{A_i} \xi = 0, i = 1, \ldots, g \right\} \subset G_{\Sigma}.$$ 

Let us quickly recall the following definition of Bergman kernels:

Definition 2.5.8 A Bergman kernel is a meromorphic bi-differential $B = B(p, q)$ on $\Sigma \times \Sigma$ with zero residue poles of order 2 along the diagonal $p = q$ and holomorphic elsewhere. We say that the Bergman kernel $B = B(p, q)$ is normalized with respect to the chosen $A$-periods if

$$B(p, q) =_{p=q} \frac{dz(p)dz(q)}{(z(p) - z(q))^2} + \text{holomorphic}, \quad \oint_{p \in A_i} B(p, q) = 0, i = 1, \ldots, g.$$ 

Remark 2.5.9 Given a curve $\Sigma$ and a choice of $A, B$ symplectic basis cycles, the normalized Bergman kernel is unique. This is because if $B$ and $B'$ are normalized Bergman kernels then $(B - B')(p, q)$ is holomorphic in $p$ with zero $A$-periods for all $q$. By the explicit construction via Riemann Theta function we find that the normalized Bergman kernels also satisfy the following properties:

$$B(p, q) = B(q, p), \quad \oint_{p \in B_i} B(p, q) = 2\pi i \omega_i(q)$$

where $\omega_i$ are the normalized holomorphic forms on $\Sigma$.

Definition 2.5.10 Let $B(p, q)$ be the normalized Bergman kernel on $\Sigma$. For any $k \in \mathbb{Z}_{\geq 1}$ and $\alpha \in \text{Ram}$ we define the meromorphic differential form on $\Sigma$:

$$e^{k, \alpha} := \frac{1}{2\pi i k} \oint_{z_{\alpha} = 0} \frac{B(\cdot, q(z_{\alpha}))}{z_{\alpha}^k}.$$
Using the standard local coordinates \(z_\alpha\) and \(z_\beta\) of \(\Sigma \cap U_\alpha\) and \(\Sigma \cap U_\beta\) respectively, \(\alpha, \beta \in \text{Ram}\), the local series expansion of \(B(p, q)\) for \(p \in \Sigma \cap U_\alpha\) and \(q \in \Sigma \cap U_\beta\) is given by

\[
B(z_\alpha(p), z_\beta(q)) = \frac{\delta_{\alpha\beta} dz_\alpha(p) dz_\beta(q)}{(z_\alpha(p) - z_\beta(q))^2} + \sum_{i,j=1}^\infty p(i,\alpha)(j,\beta) z_\alpha^{i-1}(p) z_\beta^{j-1}(q) dz_\alpha(p) dz_\beta(q)
\]  

(2.56)

for some symmetric tensor \(p(i,\alpha)(j,\beta) = p(j,\beta)(i,\alpha)\). We obtain the following easy fact about \(e^{k,\alpha}\):

**Lemma 2.5.11** Let \(e^{k,\alpha}\) be a meromorphic differential form on \(\Sigma\) as given by Definition 2.5.10 Then \(e^{k,\alpha}\in V_\Sigma\) and

\[
i(e^{k,\alpha}) = [\alpha] \otimes \frac{dz_\alpha}{z_\alpha} + \sum_{k, \alpha, \beta \in \text{Ram}} \frac{1}{k} \sum_{\alpha'} p(k,\alpha)(k',\alpha') \frac{dz_\alpha'}{z_\alpha'} \in W_{\Sigma}^\text{Ram}
\]

(2.57)

**Proof:** The expansion (2.57) is obtained from integrating the series expansion (2.56). This shows that \(e^{k,\alpha}\) is holomorphic everywhere except for a pole of order \(k+1\) at \(r_\alpha\) with zero residue. Deform \(A\)-cycles to avoid intersection with \(r_\alpha\), then \(\oint_{p \in A} e^{k,\alpha}(p) = \oint_{p \in A} B(p, q(z_\alpha)) = 0\) because the Bergman kernel is normalized. \(\square\)

**Remark 2.5.12** Note that the definition of \(e^{k,\alpha}\) implicitly depends on our choice of the Bergman kernel (since we are using the normalized Bergman kernel this is equivalent to our choice of \(A, B\) symplectic basis cycles) and the standard local coordinate \(z_\alpha\) (which is equivalent to our choice of the collection of \((\mathcal{F}, \Omega_\Sigma)\)-charts \(U_{\text{Ram}}\)).

**Lemma 2.5.13** Let \(|\Sigma| \in B\). If \(\xi_\alpha = \sum_{k=1}^\infty \xi_{\alpha,k} z_\alpha^{-k} dz_\alpha \in V_{\text{Airy}}^\alpha\) then \(\bar{\xi}_\alpha = \sum_{k=1}^\infty \bar{\xi}_{\alpha,k} e^{k,\alpha} \in V_\Sigma\). The principal part of \(i_{\alpha'}(\xi_\alpha)\) is \(\delta_{\alpha\alpha'}\bar{\xi}_\alpha\) and for any path \(C \subset \Sigma \setminus \cup_{\alpha' \in \text{Ram}} D_{\alpha', \zeta}(\Sigma)\), we have

\[
\int_C \bar{\xi}_\alpha = \int_C \sum_{k=1}^\infty \xi_{\alpha,k} e^{k,\alpha} = \int_C \sum_{k=1}^\infty \xi_{\alpha,k} e^{k,\alpha}
\]

**Proof:** We have that \(\xi_\alpha = \sum_{k=1}^\infty \sum_{k=1}^\infty \xi_{\alpha,k} z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha}\) converges absolutely uniformly for \(|z_\alpha| > \epsilon_\alpha\) for some \(\epsilon_\alpha < \epsilon_\alpha\). Therefore,

\[
\sum_{k=1}^\infty \xi_{\alpha,k} z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha} = -\sum_{k=1}^\infty \int \xi_{\alpha,k} z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha} = -\sum_{k=1}^\infty \int \xi_{\alpha,k} z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha}
\]

(2.58)

converges absolutely uniformly for \(|z_\alpha| > \epsilon_\alpha\), because integration of a power series does not change its radius of convergence. Then by using the Bergman kernel \(B(p, q)\) on \(\Sigma\) we define

\[
\xi_\alpha(p) := \int_{z_\alpha \in \partial D_{\alpha, \epsilon_\alpha}} \left( \sum_{k=1}^\infty \frac{\xi_{\alpha,k}}{k z_\alpha^k} \right) B(p, q(z_\alpha)) = \int_{z_\alpha \in \partial D_{\alpha, \epsilon_\alpha}} \frac{B(p, q(z_\alpha))}{z_\alpha^k} \sum_{k=1}^\infty \frac{\xi_{\alpha,k}}{k z_\alpha^k}
\]

where the term-by-term integration is allowed due to the absolute uniform convergence. Therefore, \(\bar{\xi}_\alpha\) is holomorphic for all \(p \in \Sigma \setminus D_{\alpha, \epsilon_\alpha} \supset \Sigma \setminus \cup_{\alpha' \in \text{Ram}} D_{\alpha', \epsilon_\alpha}\), but diverges as \(p\) approaches the integration path \(\partial D_{\alpha, \epsilon_\alpha}\). The principal part of \(\bar{\xi}_\alpha\) is \(z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha}\) so the principal part of \(i_{\alpha'}(\xi_\alpha)\) is \(\xi_\alpha\) if \(\alpha' = \alpha\) and zero otherwise. Given any path \(C \subset \Sigma \setminus \cup_{\alpha' \in \text{Ram}} D_{\alpha', \zeta}(\Sigma)\) we have

\[
\int_C \xi_\alpha(p) = \int_{p \in C} \left( \int_{z_\alpha \in \partial D_{\alpha, \epsilon_\alpha}} \left( \sum_{k=1}^\infty \frac{\xi_{\alpha,k}}{k z_\alpha^k} \right) B(p, q(z_\alpha)) \right)
\]

\[
= \sum_{k=1}^\infty \xi_{\alpha,k} \int_{z_\alpha \in \partial D_{\alpha, \epsilon_\alpha}} \int_{p \in C} \frac{B(p, q(z_\alpha))}{z_\alpha^k} = \sum_{k=1}^\infty \xi_{\alpha,k} \frac{1}{2\pi i k} \int_{z_\alpha \in \partial D_{\alpha, \epsilon_\alpha}} \frac{B(p, q(z_\alpha))}{z_\alpha^k}
\]

\[
= \sum_{k=1}^\infty \xi_{\alpha,k} \int_{p \in C} e^{k,\alpha}(p).
\]

We have used the fact that \(C\) do not intersect with \(\partial D_{\alpha, \epsilon_\alpha}\), so the order of integrations can be permuted. The integration can be done term-by-term because \(\sum_{k=1}^\infty \xi_{\alpha,k} z_\alpha^{-k} \frac{dz_\alpha}{z_\alpha}\) converges absolutely uniformly for \(|z_\alpha| > \epsilon_\alpha\). Let \(C = \partial D_{\alpha, \epsilon_\alpha}\) then \(\oint_{\partial D_{\alpha, \epsilon_\alpha}} \bar{\xi}_\alpha = \sum_{k=1}^\infty \xi_{\alpha,k} \oint_{\partial D_{\alpha, \epsilon_\alpha}} e^{k,\alpha} = 0\). On the other hand, let \(C = A_i\) then \(\oint_{A_i} \bar{\xi}_\alpha = \sum_{k=1}^\infty \xi_{\alpha,k} \oint_{A_i} e^{k,\alpha} = 0\). Therefore, we conclude that \(\bar{\xi}_\alpha \in V_\Sigma\). \(\square\)
Recall the definition of \( L_{\text{Airy}}^M \subset W_{\text{Airy}}^M \) from Section 2.4.2 and define \( L_{\text{Airy}}^\bullet := \prod_{\alpha \in \text{Ram}} L_{\text{Airy}}^{M_{\alpha}} \subset W_{\text{Airy}}^\bullet \). We note that \( T_0L_{\text{Airy}}^\bullet = \prod_{\alpha \in \text{Ram}} T_0L_{\text{Airy}}^{M_{\alpha}} \) or more explicitly:

\[
T_0L_{\text{Airy}}^\bullet = \left\{ \xi = \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \xi_\alpha \mid \xi_\alpha(z_\alpha) \in z_\alpha \mathbb{C}[[z_\alpha]] \frac{dz_\alpha}{z_\alpha}, \xi_\alpha(z_\alpha) \text{ converges for } |z_\alpha| < M_\alpha \text{ for some } M_\alpha > M_\alpha \right\} \subset W_{\text{Airy}}^\bullet,
\]

is a Lagrangian subspace of \( W_{\text{Ram}}^\bullet \).

**Lemma 2.5.14** For any \([\Sigma] \in \mathcal{B}\) we have

\[
W_{\Sigma}^\bullet = W_{\text{Ram}}^\bullet = V_{\Sigma} \oplus T_0L_{\text{Airy}}^\bullet.
\]

Additionally, if \( \xi \in V_{\Sigma} \) and the principal part of \( i_\alpha(\xi) \) is \( \sum_{k=1}^{\infty} \xi_\alpha,k z^{-k} \frac{dz_\alpha}{z_\alpha} \in V_{\alpha,\text{Airy}}^\bullet \) then it can be written as \( \xi = \sum_{\alpha \in \text{Ram}} \xi_\alpha,k e^{\alpha,k} \).

**Proof:** If \( \xi \in V_{\Sigma} \) is such that \( i_\alpha(\xi) \) has no principal part for all \( \alpha \in \text{Ram} \) then it must be holomorphic on \( \Sigma \). Therefore, \( \int_{A_\alpha} \eta = 0, \) \( i = 1, \ldots, g \) which implies that \( \eta = 0 \). This shows \( V_{\Sigma} \cap T_0L_{\text{Airy}}^\bullet = \{0\} \). To show that \( V_{\Sigma} \oplus T_0L_{\text{Airy}}^\bullet = W_{\text{Airy}}^\bullet \) we consider any given \( \xi = (\xi_\alpha \in \text{Ram}) \in W_{\text{Airy}}^\bullet \) where \( \xi_\alpha \in z^{-1}_\alpha \mathbb{C}[[z^{-1}_\alpha]] \frac{dz_\alpha}{z_\alpha} \oplus z_\alpha \mathbb{C}[[z_\alpha]] \frac{dz_\alpha}{z_\alpha} \) converges absolutely for \( \bar{\epsilon}_\alpha < |z_\alpha| < M_\alpha \) for some \( \bar{\epsilon}_\alpha < \epsilon_\alpha < M_\alpha < M_\alpha \). Let \( \xi_\alpha,P = \sum_{k=1}^{\infty} \bar{\epsilon}_k z^{-k} \frac{dz_\alpha}{z_\alpha} \in V_{\alpha,\text{Airy}}^\bullet \) be the principal part of \( \xi_\alpha \). By Lemma 2.5.13 we have \( \xi_P := \sum_{\alpha \in \text{Ram}} \xi_\alpha,P = \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_\alpha,k e^{\alpha,k} \in V_{\Sigma}^\bullet \) and the principal part of \( i_\alpha(\xi) \) is \( \bar{\epsilon}_P \). On the other hand, because \( \Sigma \in \mathcal{B}_{\Sigma} \) we have that \( i_\alpha(\xi) \) converges absolutely for \( \bar{\epsilon}_\alpha < |z_\alpha| < M_\alpha \) where \( M_\alpha \) is such that \( D_{\alpha,M_\alpha}(\Sigma) \subset D_{\alpha,\bar{\epsilon}_\alpha}(\Sigma) \subset \Sigma \cap U_\alpha \). It follows that \( \xi_\alpha = i_\alpha(\xi_P) \) has zero principal part and converges absolutely for \( |z_\alpha| < \min(M_\alpha, M_\alpha) \). Therefore \( \xi - i_\alpha(\xi_P) \in T_0L_{\text{Airy}}^\bullet \) which proves that \( W_{\text{Airy}}^\bullet = V_{\Sigma} \oplus T_0L_{\text{Airy}}^\bullet \). Besides, if \( \xi \in V_{\Sigma} \), then \( \xi - i_\alpha(\xi_P) \) is holomorphic on \( \Sigma \) with \( \int_{A_\alpha}(\xi - i_\alpha(\xi_P)) = 0 \) for all \( i = 1, \ldots, g \) which means \( \xi = \xi_P = \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_\alpha,k e^{\alpha,k} \).

**Corollary 2.5.15** For any \([\Sigma] \in \mathcal{B}\) we have

\[
G_{\Sigma} = \Sigma \oplus \Gamma(\Sigma, \Omega_{\Sigma}^1),
\]

In particular, any \( \xi \in G_{\Sigma} \) with the principal part of \( \xi(\xi) \) given by \( \sum_{k=1}^{\infty} \xi_\alpha,k z^{-k} \frac{dz_\alpha}{z_\alpha} \in \mathbb{C}[[z_\alpha]] \frac{dz_\alpha}{z_\alpha} \) and \( \alpha := \int_{A_\alpha} \xi \) can be written as \( \xi = \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_\alpha,k e^{\alpha,k} + \sum_{k=1}^{\infty} a^k \omega_k \), where \( \omega_k \) are the normalized holomorphic forms on \( \Sigma \).

**Proof:** In fact, \( G_{\Sigma} = V_{\Sigma} \oplus \Gamma(\Sigma, \Omega_{\Sigma}^1) \) follows directly from the Definition 2.5.4 and Definition 2.5.7 of \( G_{\Sigma} \) and \( V_{\Sigma} \). This is because for any \( \xi \in G_{\Sigma} \), we have \( \bar{\xi} = \bar{\xi} - \sum_{k=1}^{\infty} a^k \omega_k \in V_{\Sigma} \), hence \( V_{\Sigma} + \Gamma(\Sigma, \Omega_{\Sigma}^1) = G_{\Sigma} \). We also know that \( V_{\Sigma} \cap \Gamma(\Sigma, \Omega_{\Sigma}^1) = \{0\} \) because any global holomorphic form with zero \( A \)-periods is zero. The rest of the Corollary follows from applying Lemma 2.5.14 to \( \xi \in V_{\Sigma} \).

**Corollary 2.5.17** \( V_{\Sigma} \) is a Lagrangian complement of \( T_0L_{\text{Airy}}^\bullet \) in \( W_{\text{Airy}}^\bullet \).

**Proof:** We already know from Lemma 2.5.14 that \( V_{\Sigma} \) is a complement of \( T_0L_{\text{Airy}}^\bullet \). Using 2.5.5, it is clear that for any \( \xi_1, \xi_2 \in V_{\Sigma} \) we would have \( \Omega_{\text{Airy}}(\xi_1, \xi_2) = 0 \) because \( \int_{A_\alpha} \xi_j = 0, i = 1, \ldots, g, j = 1, 2 \). Suppose there exists \( \xi_2 \in W_{\text{Airy}}^\bullet \) such that \( \Omega_{\text{Airy}}(\xi_1, \xi_2) = 0 \) for all \( \xi_1 \in V_{\Sigma} \). Then by Lemma 2.5.14 we can write \( \xi_2 = v + l \) where \( v \in V_{\Sigma}, l \in T_0L_{\text{Airy}}^\bullet \) but then \( \Omega_{\text{Airy}}(\xi_1, l) = \Omega_{\text{Airy}}(\xi_1, v + l) = \Omega_{\text{Airy}}(\xi_1, \xi_2) = 0, \forall \xi_1 \in V_{\Sigma} \) because \( \Omega_{\text{Airy}}(\xi_1, v) = 0 \). Since we also have \( \Omega_{\text{Airy}}(l, l) = 0 \) for all \( l \in T_0L_{\text{Airy}}^\bullet \), this can only be true if \( l = 0 \), i.e. \( \xi_2 \in V_{\Sigma} \), because \( \Omega_{\text{Airy}} \) is non-degenerate. So we have that \( V_{\Sigma} \) is a Lagrangian subspace of \( W_{\text{Ram}}^\bullet \) i.e. \( V_{\Sigma}^\perp = V_{\Sigma} \).
Proposition 2.5.18 ([25, Proposition 7.1.3]) For any $\Sigma \in B$, the vector space $G_\Sigma$ is a coisotropic subspace of $W_{\text{Ram}}(\Sigma)$ with the perpendicular subspace $G_\Sigma^\perp$ given by

$$G_\Sigma^\perp = \lim_{\epsilon_\alpha \to 0} d\Gamma(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}, \Omega_\Sigma) \subseteq G_\Sigma.$$ 

Proof: From $V_\Sigma \subset G_\Sigma$ and Corollary 2.5.17 we have that $G_\Sigma^\perp \subset V_\Sigma \subset G_\Sigma$. Let us find $G_\Sigma^\perp$. If $\xi \in G_\Sigma^\perp$, then $\xi \in G_\Sigma^\perp$ which means $\int_{\bar{D}_{0,\epsilon_\alpha}} \xi = 0$. Using (2.55) we can see that the only way $\Omega_{\text{Airy}}(\xi, \eta) = 0$, $\forall \eta \in G_\Sigma$ can be possible is if $f_{\bar{D}_{0,\epsilon_\alpha}} \xi = 0$, $f_{\bar{D}_{0,\epsilon_\alpha}} \eta = 0$, $i = 1, \ldots, g$. We can now define $f(p) := f_{\bar{D}_{0,\epsilon_\alpha}} \xi$ which is a holomorphic function in an open neighbourhood of $\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}$. \hfill $\square$

Proposition 2.5.19 ([25, Proposition 7.1.3]) For any $\Sigma \in B$, the symplectic reduction of $W_{\text{Ram}}(\Sigma)$ is given by $W_{\text{Ram}}(\Sigma)/G_\Sigma^\perp := G_\Sigma/G_\Sigma^\perp \cong H^1(\Sigma, \mathbb{C})$. Furthermore, the induced symplectic form $\tilde{\Omega}_{\text{Airy}}$ on the quotient $G_\Sigma/G_\Sigma^\perp$ given by

$$\tilde{\Omega}_{\text{Airy}}([\xi_1], [\xi_2]) := \Omega_{\text{Airy}}(\xi_1, \xi_2)$$

(2.59)

coincides with the symplectic form $\Omega_{\text{H}}$ on $H_\Sigma$ as given in (2.5).

Proof: First, we will show that $G_\Sigma/G_\Sigma^\perp$ is isomorphic to the deRham cohomology group $H_\Sigma = H^1(\Sigma, \mathbb{C})$. For any set $\{\epsilon_\alpha \in \text{Ram}\}$ such that $\epsilon_\alpha < \epsilon_\alpha$, $\alpha \in \text{Ram}$ we have the presentation

$$H_\Sigma = H^1(\Sigma, \mathbb{C}) \cong \left\{ \xi \in \Gamma(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}, \Omega_\Sigma) \mid \int_{\bar{D}_{0,\epsilon_\alpha}} \xi = 0 \right\}.$$ 

(2.60)

To obtain this, we use Mayer–Vietoris sequence to get $H^1(\Sigma, \mathbb{C}) \cong \{ \xi \in H^1(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}, \mathbb{C}) \mid \int_{\bar{D}_{0,\epsilon_\alpha}} \xi = 0 \}$. Then we use the fact that non-compact Riemann surfaces such as $\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}$ is a Stein manifold [17, Behnke and Stein, Section 2.2], hence coherent sheaves are $\Gamma$-acyclic on $\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}$ by Cartan’s theorem B [17, Theorem 2.4.1]. Therefore, $H^1(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}, \mathbb{C}) \cong H^1(\Sigma \setminus \cup_{\alpha \in \text{Ram}} \overline{D}_{0,\epsilon_\alpha}, \Omega_\Sigma)$, i.e. deRham cohomology can be computed as a sheaf cohomology of $\mathbb{C}$ using the $\Gamma$-acyclic resolution $0 \to \mathbb{C} \to \Omega_\Sigma^\bullet$ (see, for example, [6, Corollary 2.5.3]), which implies (2.60). Recall that the direct limit functor preserves short exact sequences. Therefore, taking the direct limit of (2.60) and compare the result to the explicit expression of $G_\Sigma$ and $G_\Sigma^\perp$ in Definition 2.5.4 and Proposition 2.5.18, we have $H^1(\Sigma, \mathbb{C}) \cong G_\Sigma/G_\Sigma^\perp$ as claimed.

Next, we show that $\tilde{\Omega}_{\text{Airy}}$ is a symplectic form on $H_\Sigma$. If $\xi_1 = \xi_1 + df_1$, $\xi_2 = \xi_2 + df_2$ then $\tilde{\Omega}_{\text{Airy}}([\xi_1], [\xi_2]) = \tilde{\Omega}_{\text{Airy}}(\xi_1 + df_1, \xi_2 + df_2) = \tilde{\Omega}_{\text{Airy}}(\xi_1, \xi_2) = \tilde{\Omega}_{\text{Airy}}([\xi_1], [\xi_2])$, so $\tilde{\Omega}_{\text{Airy}}$ is well-defined. It is non-degenerate because if $[\xi] \in H_\Sigma$ is such that $\tilde{\Omega}_{\text{Airy}}([\xi], [\eta]) = 0$ for all $[\eta] \in H_\Sigma$ then $\tilde{\Omega}_{\text{Airy}}(\xi, \eta) = 0$ for all $\eta \in G_\Sigma$ implying that $\xi \in G_\Sigma^\perp$ and hence $[\xi] = 0$. This proves that $H_\Sigma$ is a symplectic vector space with the induced symplectic form $\tilde{\Omega}_{\text{Airy}}$. Using (2.55) and Lemma 2.1.14 we can see that $\tilde{\Omega}_{\text{Airy}}$ coincides with $\Omega_{\text{H}}$ as claimed. \hfill $\square$

Given $\xi \in G_\Sigma$, the cohomology class $[\xi] \in H^1(\Sigma, \mathbb{C})$ is completely determined by the $A$ and $B$ periods of $\xi$. In other words, we have a map $[\cdot] : G_\Sigma \to H_\Sigma$ given by $\xi \mapsto (H_1(\Sigma, \mathbb{C}) \ni [\xi] \mapsto f_{\bar{D}_{0,\epsilon_\alpha}} \xi)$. Proposition 2.5.19 tells us that this map is surjective, in other words, there are enough differential forms on $G_\Sigma$ to represent every cohomology classes in $H^1(\Sigma, \mathbb{C})$.

Remark 2.5.20 Similarly, it has been shown in [25, Proposition 7.1.3] that $G^\text{mer}_\Sigma$ is a coisotropic subspace of $W^\text{Ram}_{\text{Airy}}$ (see Section 2.5.4 for the definition of $W^\text{Ram}_{\text{Airy}}$) with

$$(G^\text{mer}_\Sigma)_\perp = \left\{ df \mid f \in \Gamma \left( \Sigma, \mathcal{O}_\Sigma \left( \sum_{\alpha \in \text{Ram}} nr_\alpha \right) \right) \right\}, \text{ for some } n \in \mathbb{Z}_{\geq 0} \subseteq G^\text{mer}_\Sigma$$

and we have $G^\text{mer}_\Sigma / (G^\text{mer}_\Sigma)_\perp \cong H_\Sigma$.

At last, let us define the vector bundle $G \to B$ with fiber over each point $\Sigma \in B$ given by $G_\Sigma$.

For any given point $\Sigma \in B$, there exists an open neighbourhood $B_\Sigma \subset B$ of $\Sigma$ such that $A, B$ symplectic basis cycles can be chosen consistently for all $\Sigma' \in B_\Sigma$ (see Remark 2.1.13). Let us also assume that $B_\Sigma$ is sufficiently small that $\tilde{\Omega}^2_{\text{Ram}}$ is satisfied for some $\{\epsilon_\alpha \in \text{Ram}\}$, $\{M_\alpha \in \text{Ram}\}$ and a collection of $(F, \Omega_\Sigma)$-charts $U_{\text{Ram}}^\Sigma$. It follows that the normalized holomorphic forms $\{\omega_{i=1,\ldots,g}\}$ and the normalized Bergman kernel $B(p, q)$
are defined on every curve $[\Sigma'] \in B_\Sigma$ consistently throughout $B_\Sigma$. For each $[\Sigma'] \in B_\Sigma$, let us denote by $\{\omega_{\Sigma, \Sigma'}^k\}, (\xi_{\Sigma, \Sigma'})$ the set of normalized holomorphic forms and the set of meromorphic differentials on $\Sigma'$ defined by the normalized Bergman kernel (Definition 2.5.10) corresponding to the given consistent choice of $A, B$ symplectic basis cycles on $B_\Sigma$. Let the topology on $G_\Sigma$ be induced from the norm

$$\|\xi\|_{G_\Sigma} := \sqrt{\sum_{\alpha \in \text{Ram}} \sup_{p \in K_{\Sigma}, \omega_{\alpha, \Sigma}} |(\xi)(p)|^2 z_{\alpha}(p)^2}.$$  

and recall from Corollary 2.5.16 any $\xi \in G_\Sigma$ can be written as $\xi = \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_{k, \alpha} e_{\Sigma, \Sigma'}^k + \sum_{k=1}^{\infty} d_{0} \omega_{k, \Sigma'}$. Then, given $[\Sigma_1], [\Sigma_2] \in B_\Sigma$ we define a homeomorphism $G_{\Sigma_1} \cong G_{\Sigma_2}$ by

$$\sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_{k, \alpha} e_{\Sigma, \Sigma_1} + \sum_{k=1}^{q} a_{k} \omega_{k, \Sigma_1} \leftrightarrow \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} \xi_{k, \alpha} e_{\Sigma, \Sigma_2} + \sum_{k=1}^{q} a_{k} \omega_{k, \Sigma_2}. \quad (2.61)$$

**Remark 2.5.21** It is important that $B_\Sigma$ satisfies $2.5.2.2$ for some $\{e_{\alpha \in \text{Ram}}, \{M_{\alpha \in \text{Ram}}, U^\alpha_{\text{Ram}}, \text{otherwise}, the Definition 2.5.10 of $e_{\Sigma, \Sigma'}^k$, and the definition of $\|\xi\|_{G_\Sigma}$ will not make sense.

Equip $B_\Sigma \times G_\Sigma$ with the product topology and assign a topology to the set $G|_{B_\Sigma} := \{(\Sigma'), \xi \mid \Sigma' \in B_\Sigma, \xi \in G_\Sigma\}$ such that $G|_{B_\Sigma} \cong B_\Sigma \times G_\Sigma$, induced from (2.61), is a homeomorphism over the base $B_\Sigma$. Then, it follows that $G := \bigcup_{\Sigma' \in B} G|_{B_\Sigma}$ with the canonical projection $\pi : G \to B$ is a vector bundle with fiber over each point $[\Sigma] \in B$ given by $\pi^{-1}(\Sigma) = G_{\Sigma}$ and $G|_{B_\Sigma} \cong B_\Sigma \times G_\Sigma$ giving a local trivialization over each $B_\Sigma$.

**Definition 2.5.22** Let $(G \to B, \nabla_F)$ be the vector bundle $G := \bigcup_{\Sigma' \in B} G|_{B_\Sigma}$ with fiber $G_{\Sigma'}$ over each point $[\Sigma] \in B$ and equipped with the connection $\nabla_F : \Gamma(B, G) \to \Gamma(B, T^*B \otimes G)$ given by the differentiation along a leaf of the foliation $F$.

Note that for any open subset $B' \subseteq B$ we denote by $\Gamma(B', G)$ the set of holomorphic sections of $G$ on $B'$.

We will mostly be interested in the small deformations of the curve $\Sigma_0$, therefore, it is sufficient to consider the restriction of $G$ to the open neighbourhood $B_{\Sigma_0} \subseteq B$ of $[\Sigma_0]$, where $B_{\Sigma_0}$ along with $\{e_{\alpha \in \text{Ram}}, \{M_{\alpha \in \text{Ram}}, U^\alpha_{\text{Ram}}, \text{otherwise}, the Definition 2.5.10 of $e_{\Sigma, \Sigma'}^k$, and the definition of $\|\xi\|_{G_\Sigma}$ will not make sense.

Equip $B_\Sigma \times G_{\Sigma_0}$ with the product topology and assign a topology to the set $G|_{B_{\Sigma_0}} := \{(\Sigma'), \xi \mid \Sigma' \in B_{\Sigma_0}, \xi \in G_{\Sigma_0}\}$ such that $G|_{B_{\Sigma_0}} \cong B_{\Sigma_0} \times G_{\Sigma_0}$, induced from (2.61), is a homeomorphism over the base $B_{\Sigma_0}$. Then, it follows that $G := \bigcup_{\Sigma' \in B_{\Sigma_0}} G|_{B_{\Sigma_0}}$ with the canonical projection $\pi : G \to B_{\Sigma_0}$ is contractible by 2.5.2.2, the restriction of $G$ to $B_{\Sigma_0}$ is a trivial vector bundle which we denote by $(G \to B_{\Sigma_0}, \nabla_F)$. Similarly, the trivial vector sub-bundles of $G \to B_{\Sigma_0}$: $G^{\perp} \to B_{\Sigma_0}$ with fiber $G^\Sigma_{\Sigma_0}$ and $V \to B_{\Sigma_0}$ with fiber $V_{\Sigma_0}$ over $[\Sigma] \in B_{\Sigma_0}$ may be constructed.

Let us recast some definitions and results in this section as follows. We have an injective vector bundle morphism $i : G \to W^\text{Ram}$ covering the map $\gamma : B_{\Sigma_0} \to \text{Disc}_{\text{Ram}}$ given by (2.53), such that $i$ restricted to the fiber over any point $[\Sigma] \in B_{\Sigma_0}$ is $i : \Sigma \to W^\text{Ram}_{\Sigma}$ (2.54) (see Figure 2.5.6). Therefore, $G$ is a vector sub-bundle of $W^\text{Ram}$, in fact by Proposition 2.5.18 it is a coisotropic vector sub-bundle. Note that it is a lot less straightforward to define a vector bundle morphism $i : G \to W^\text{Ram}$ had we considered $G \to B_{\Sigma_0}$ instead of its restriction $G \to B_{\Sigma_0}$, for instance, $\gamma : B \to \text{Disc}_{\text{Ram}}$ is not defined unless $B$ satisfies 2.5.2.2. Proposition 2.5.19 can be restated as an isomorphism of vector bundles $G/G^\perp \cong H$. We define $[\Sigma] : G \to H$ to be the morphism of vector bundle given fiber-wise by the natural projection $G_{\Sigma} \to G_{\Sigma}/G^\Sigma_{\Sigma} \cong H_{\Sigma} \cong H^1(\Sigma, C)$ which sends any differential form $\xi \in G_{\Sigma}$ to its cohomology class $[\xi] \in H^1(\Sigma, C)$ (see Figure 2.5.6).

### 2.5.4 The Ram product residue constraints

So far, the residue constraints were only introduced on a disc with only a single ramification point. Since there are more than one ramification points on $\Sigma$, we will need to consider a $[\text{Ram}]$ copies of the residue constraints. The purpose of this section is to fix the needed notations regarding the Ram product residue constraints Airy structure.

Consider the Airy structure obtained as a product of the residue constraints Airy structures introduced in Section 2.3. Let $I := \mathbb{Z}_{>0} \times \text{Ram}$ and let $V^\text{Ram}_{\text{Airy}} = \prod_{\alpha \in \text{Ram}} V^\text{Ram}_{\text{Airy}} = \sum_{\alpha \in \text{Ram}} [\alpha] \otimes z^{-1} \mathbb{C}[z^{-1}] \frac{dz}{z}$ be a discrete vector space with a basis $\{e^{k,1,2,\ldots,\alpha \in \text{Ram}} : [\alpha] \otimes z^{-k} \frac{dz}{z}\}$. The continuous dual space is given by $(V^\text{Ram}_{\text{Airy}})^* := \prod_{\alpha \in \text{Ram}} V_{\text{Airy}}^* = \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \mathbb{C}[z] \frac{dz}{z}$ with a basis $\{f_{k,1,2,\ldots,\alpha \in \text{Ram}} : [\alpha] \otimes kz \frac{dz}{z}\}$. Define the Tate space

$$W^\text{Ram}_{\text{Airy}} := \left\{ \eta = \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \eta_\alpha \mid \eta_\alpha \in \mathbb{C}((z))dz, \text{Res}_{z=0}\eta_\alpha = 0, \alpha \in \text{Ram} \right\} = V^\text{Ram}_{\text{Airy}} \oplus (V^\text{Ram}_{\text{Airy}})^*$$

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with the symplectic form $\Omega_{Airy}(\{a_1\} \otimes \xi_1, \{a_2\} \otimes \xi_2) = \delta_{a_1, a_2} R_{\xi_1} \xi_2 = 0 (\xi_1 \neq \xi_2)$. We define the $[\text{Ram}]$ product residue constraints Airy structure $\{(H_{Airy})_{k=1,2,3,\ldots, \alpha \in \text{Ram}}\}$ on $V^{[\text{Ram}]}_{\text{Airy}}$ by

\[
(H_{Airy})_{2n,\alpha}(w) = R_{\xi_1} \xi_2 = \left( \frac{w(z)}{2\pi z^2} \right)^{\alpha} z^{2n} d(z^2), \quad n = 1, 2, 3, \ldots
\]

where $w := \sum_{\alpha \in \text{Ram}} \sum_{k=1}^{\infty} (z^{k,\alpha} f_{k,\alpha} + y_{k,\alpha} x^{k,\alpha}) \in W^{[\text{Ram}]}_{\text{Airy}}$. We may write (2.62) in the standard form (2.19):

\[
(H_{Airy})_{i,\alpha} = -y_{i,\alpha} + \sum_{\beta, \gamma \in \text{Ram}} \sum_{j=1}^{\infty} (a_{Airy})((i,\alpha),(j,\beta),(k,\gamma)) x^{j,\beta} x^{k,\gamma} + \sum_{\beta, \gamma \in \text{Ram}} \sum_{j=1}^{\infty} (c_{Airy})((j,\alpha),(k,\beta)) y_{j,\alpha} y_{k,\gamma},
\]

and express the residue constraints Airy structure as $\{(V^{[\text{Ram}]}_{\text{Airy}}), A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}\}$ where

\[
A_{\text{Airy}} := (a_{Airy})((i,\alpha),(j,\beta),(k,\gamma)) , \quad B_{\text{Airy}} := (b_{Airy})((i,\alpha),(j,\beta),(k,\gamma)) , \quad C_{\text{Airy}} := (c_{Airy})((i,\alpha),(j,\beta),(k,\gamma)).
\]

The corresponding quantum Airy structure is $\{(V^{[\text{Ram}]}_{\text{Airy}}), A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}\}$ where $(\epsilon_{Airy})_{i,\alpha} := \frac{1}{2\pi i} \delta_{\beta,\gamma}$ and $\epsilon_{\text{Airy}} = (\epsilon_{\text{Airy}})_{i,\alpha}$. Define the quadratic Lagrangian submanifold $L^{[\text{Ram}]}_{\text{Airy}} := \{(H_{Airy})_{i=1,2,3,\ldots, \alpha \in \text{Ram}} = 0 \} \subset W^{[\text{Ram}]}_{\text{Airy}}$ with $T_{0}^{L^{[\text{Ram}]}_{\text{Airy}}} := \sum_{\alpha \in \text{Ram}} [a] \otimes \mathbb{C}[z][d^2] = (V^{[\text{Ram}]}_{\text{Airy}})^{\ast}$. It is clear that $T_{0}L^{[\text{Ram}]}_{\text{Airy}}$ is a Lagrangian subspace of $W^{[\text{Ram}]}_{\text{Airy}}$ and that $V^{[\text{Ram}]}_{\text{Airy}}$ is a Lagrangian complement of $T_{0}L^{[\text{Ram}]}_{\text{Airy}}$.

**Remark 2.5.23** Our definitions of $W^{[\text{Ram}]}_{\text{Airy}}$ and $L^{[\text{Ram}]}_{\text{Airy}}$ are exactly the same as how $\text{Ram}$ and $\text{Ram}$ were defined in Section 7.1. Our choice of symbols came from the fact that $W^{[\text{Ram}]}_{\text{Airy}}$ and $L^{[\text{Ram}]}_{\text{Airy}}$ are the products of $\text{Ram}$ copies of $\text{Airy}$ (as given in Section 2.3 or Section 3.3) respectively, where $\text{Ram}$ denotes the number of ramification points. Finally, note that by taking Laurent expansion of any $\xi \in G^{\text{mer}}_{\Sigma}$ we obtain the inclusion $\xi : G^{\text{mer}}_{\Sigma} \hookrightarrow W^{[\text{Ram}]}_{\text{Airy}}$ can also be defined exactly as we did in (2.54).

Let us consider a new Lagrangian complement of $T_{0}L^{[\text{Ram}]}_{\text{Airy}}$:

\[
V^{\text{mer}}_{\Sigma} := \{ \xi \in G^{\text{mer}}_{\Sigma} | \int A_{\xi} = 0, i = 1, \ldots, g \}
\]

where $G^{\text{mer}}_{\Sigma}$ was given in Remark 2.5.5. Essentially, $V^{\text{mer}}_{\Sigma} \subseteq V_{\Sigma}$ is the subspace of meromorphic differential forms in $V_{\Sigma}$ with basis $\{e_{1}=1,2,3,\ldots, \alpha \in \text{Ram}\}$ where $e_{1}$ is defined in Definition 2.5.10 and note that (2.57) can be written as

\[
e^{k,\alpha} = e^{k,\alpha} + \sum_{\alpha' \in \text{Ram}} \sum_{k=1}^{\infty} \frac{1}{kk'} P^{(k,\alpha)(k',\alpha')} f_{k',\alpha'}.
\]

The gauge transformation $\{(V^{[\text{Ram}]}_{\text{Airy}}), A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}\} \rightarrow \{(V^{\text{mer}}_{\Sigma})_{\epsilon}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}\}$ associating with the choice of basis $\{\tilde{\epsilon}_{1}=1,2,3,\ldots\} := \sum_{\beta, \gamma \in \text{Ram}} \sum_{j=1}^{\infty} (d_{i,\beta})^{i,\gamma}_{j,\beta}, (d'_{i,\beta})^{i,\gamma}_{j,\beta}$ for $V^{\text{mer}}_{\Sigma}$ and $\{\tilde{\omega}_{i}=1,2,3,\ldots\} := \sum_{\alpha \in \text{Ram}} \sum_{i=1}^{\infty} (f_{i,\alpha})$ for $T_{0}L^{[\text{Ram}]}_{\text{Airy}}$ for some $\{\tilde{\epsilon}_{1}=1,2,3,\ldots\}$ $V^{[\text{Ram}]}_{\text{Airy}} \rightarrow V^{\text{mer}}_{\Sigma}$ and its inverse $(d'_{i,\beta})^{i,\gamma}_{j,\beta} : V^{\text{mer}}_{\Sigma} \rightarrow V^{[\text{Ram}]}_{\text{Airy}}$ is given by

\[
(b_{Airy})_{i,\alpha} = (a_{Airy})((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha},
\]

\[
(b_{Airy})_{i,\alpha} = (b_{Airy})((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha},
\]

\[
(c_{Airy})((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha},
\]

\[
(c_{Airy})((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha},
\]

\[
(c_{Airy})((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha},
\]

\[
(\epsilon_{Airy})_{i,\alpha} = \left( \epsilon_{\text{Airy}}((i,\alpha),(j,\alpha),(j,\alpha),(j,\alpha)) c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} c_{j,\alpha}^{\alpha} \right),
\]

where $s^{(i,\alpha)(j,\beta)} = \frac{1}{\sqrt{2\pi i}} P^{(i,\alpha)(j,\beta)}$.
Remark 2.5.24 It is easy to see that \((V_{\text{Airy}})_{\text{odd}}^{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) is a quantum Airy sub-structure of \((V_{\text{Airy}})_{\text{odd}}^{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) where \((V_{\text{Airy}})_{\text{odd}}^{\text{Ram}} := \prod_{\alpha \in \text{Ram}} (V_{\text{Airy}})_{\text{odd}} \subset V_{\text{Airy}}^{\text{Ram}}\). Likewise, let \((V_{\text{Airy}}^{\text{mer}})_{\text{odd}} \subset V_{\text{Airy}}^{\text{mer}}\) be the vector space spanned by finite linear combinations of vectors \(\{e_k=\text{odd}, \alpha \in \text{Ram}\}\) then \((V_{\text{Airy}}^{\text{mer}})_{\text{odd}}^{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) is a quantum Airy sub-structure of \((V_{\text{Airy}}^{\text{mer}}), A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\) according to Remark 2.2.30.

The consideration of the analytic residue constraints Airy structure in Section 2.4.2 straightforwardly generalizes to the case of the Ram product residue constraints Airy structure because Ram is a finite set. In particular, we treat \((2.62)\) analytically as functions \((H_{\text{Airy}})_{i, \alpha} : W_{\text{Ram}}^{\alpha, \epsilon} \to C\) and we also have that \(L_{\text{Ram}} = \{(H_{\text{Airy}})_{i, \alpha, \epsilon} = 0\} \subset W_{\text{Ram}}^{\alpha, \epsilon}\). The analytic counter-part of \((V_{\text{Ram}}^{\alpha, \epsilon})\) is obviously given by \(V_{\text{Ram}} := \prod_{\alpha \in \text{Ram}} V_{\text{Ram}}^{\alpha, \epsilon}\). It is clear that \(V_{\text{Ram}}^{\alpha, \epsilon}\) is a Lagrangian complement of \(T_0 L_{\text{Ram}}\) in \(W_{\text{Ram}} = V_{\text{Ram}}^{\alpha, \epsilon} \oplus T_0 L_{\text{Ram}}\).

According to Corollary 2.5.17, \(V_{\text{air}}\) is another Lagrangian complement of \(T_0 L_{\text{Ram}}^{\alpha, \epsilon}\). Let us use \(\{\eta^{i=1,2,3,\ldots} := \sum_{\beta \in \text{Ram}} \sum_{j=1,2} d_{j, \beta}^{\alpha, \epsilon, \beta} \}\) as a basis of \(V_{\text{air}}\) and \(\{\omega^{i=1,2,3,\ldots} := \sum_{\alpha \in \text{Ram}} \sum_{\gamma, \epsilon, \beta} c_{i, \gamma, \beta} \}\) as a basis of \(T_0 L_{\text{Ram}}^{\alpha, \epsilon}\) for some \((c_{i, \gamma, \beta})\), \((d_{j, \beta})\) satisfying Condition 2.4.17. Note that \((s_i, \gamma, \beta)\) where \(s_i = \frac{1}{2} P_{i, \gamma, \beta} - \frac{1}{2} P_{i, \gamma, \beta} - \frac{1}{2} P_{i, \gamma, \beta}\) also satisfies Condition 2.4.17 since it came from the series expansion of a Bergman kernel. Therefore, the change of the canonical basis \((c_{i, \gamma, \beta}, d_{j, \beta}) \to (\gamma, \beta)\) of \(W_{\text{Ram}}^{\alpha, \epsilon}\) is of the same type as considered in Section 2.4.2. Suppose that \(w = \sum_{\alpha \in \text{Ram}} \sum_{\gamma, \epsilon, \beta} c_{i, \gamma, \beta} \) where \(c_{i, \gamma, \beta} \) are the new canonical coordinates of \(W_{\text{Ram}}^{\alpha, \epsilon}\). Also, by Proposition 2.4.20 we have \((H_{\text{Airy}})_{i, \alpha} := \sum_{\beta \in \text{Ram}} \sum_{\gamma, \epsilon, \beta} c_{i, \gamma, \beta} (H_{\text{Airy}})_{j, \gamma, \beta} \) given by

\[
(H_{\text{Airy}})_{i, \alpha} := -\beta_i + \sum_{j=1,2} \sum_{k=1,2} (a_{\text{Airy}})_{i, j, k} \alpha^j \alpha^k + 2 \sum_{j=1,2} \sum_{k=1,2} (b_{\text{Airy}})_j^k \beta_i \beta_j + \sum_{j=1,2} \sum_{k=1,2} (\epsilon_{\text{Airy}})_j^k \beta_j \beta_k
\]

(2.65)

where \(A_{\text{Airy}} = \{(a_{\text{Airy}})_{i, j, k} \}, B_{\text{Airy}} = \{(b_{\text{Airy}})_j^k \}, C_{\text{Airy}} = \{(\epsilon_{\text{Airy}})_j^k \}\) are given by (2.63).

Remark 2.5.25 Moreover, it is straightforward to generalize Proposition 2.4.21 to the case of the Ram product residue constraints Airy structure. We conclude that if \(i_\alpha (\sum_{\gamma, \epsilon, \beta} \sum_{j=1,2} c_{i, \gamma, \beta} (H_{\text{Airy}})_{j, \gamma, \beta} ) (\alpha^j, \cdots, \alpha^K, \epsilon) \) is holomorphic in \(\{\alpha^j, \cdots, \alpha^K, \epsilon\}\) on some open neighbourhood of \((\alpha^1, \cdots, \alpha^K) = (0, \cdots, 0), |\alpha_1| > \epsilon_1\) and

\[
(H_{\text{Airy}})_{i, \alpha} \{\alpha^1, \cdots, \alpha^K, \epsilon, K = 0\}, (\beta_{i=1,2,3,\cdots}, (\alpha^1, \cdots, \alpha^K)) = 0
\]

then \(\beta_i = (\partial_i S_0)_{i, \epsilon, K = 0}\). Where \(S_0 = \sum_{n=1}^{\infty} S_{0, n} \in \Pi_{n=1}^{\infty} \text{Sym}_n (V_{\text{Airy}}^{\text{mer}})\) is the genus zero part of the ATR output using the quantum Airy structure \((V_{\text{Airy}}^{\text{mer}}), A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}})\).

2.5.5 Connection \(\nabla_F\) and parallel transport on \(G \to B_{\Sigma_0}\)

In this section, we are going to more carefully examine the connection \(\nabla_F\) and discuss the parallel transport on \(G \to B_{\Sigma_0}\). For now, let \(\{\alpha \in \text{Ram}\}, \{M_{\alpha} \in \text{Ram}\}, \{U_{\text{Ram}} = \{U_{i, j} \in \text{Ram}, x_{\alpha \in \text{Ram}, J_0 \in \text{Ram}}\}\) and an open neighbourhood \(B_{\Sigma_0} \subseteq B\) of \(B_{\Sigma_0} \in B\) be chosen such that (2.5.24) and (2.5.22) are satisfied. Recall from Definition 2.5.22 that \(\nabla_F\) is given by the differentiation along a leaf of the foliation \(F\). Let us verify that this indeed defines a connection on \(G \to B_{\Sigma_0}\) which is flat.

Lemma 2.5.26 For any section \(\xi \in (B_{\Sigma_0}, G), \) we have \(\nabla_F \xi \in (B_{\Sigma_0}, T^* B \otimes G)\).

Proof: Consider \(\Sigma \in B_{\Sigma_0}.\) Let \(U := \{U_{r_{\alpha, \sigma}} \} \) be a collection of \((F, \Omega_F)\)-charts covering \(\Sigma \setminus U_{\alpha \in \text{Ram}} D_{\alpha, \epsilon, \gamma}(\Sigma)\) where \(\gamma \cap U_{\alpha}\) are bi-holomorphic to a simply-connected open subset of \(\Sigma\) with \(x_{\alpha}\) as a local coordinate and \(\sigma\) is some finite index set. It follows that \(dx_{\alpha}|^{\Sigma \setminus U_{\alpha}} \neq 0\) and so \(\partial_{\alpha}(\Sigma) \notin \partial_{\epsilon \sigma} \Sigma \cap U_{\alpha}\) for all \(\alpha \in \text{Ram}.\)

Let \(\{u^1, \ldots, u^n\}\) be coordinates of \(B_{\Sigma_0}\) (this exists due to the condition (2.5.21)). Given a section \(\xi \in (B_{\Sigma_0}, G)\), \(\xi \in G_{\Sigma}\) and a tangent vector \(v = \sum_{k=1}^{n} v^k \frac{\partial}{\partial x^k} \in T_{[\Sigma]} B_{\Sigma_0}\) then for each \(p \in \sigma\) we have \(v_r \nabla_F \xi|_{\Sigma \setminus U_{\alpha}} = \)
\[ \sum_{a=1}^{g} v^a \frac{\partial}{\partial x^a} |_{x_0=\text{const}}(\xi^a \xi^b \xi^c) \]  

Using \( x_p \) as a local coordinate on \( \Sigma \cap U_p \) and write \( \xi|_{\Sigma \cap U_p} = \xi_p(x_p, u)dx_p \). It follows that \( \iota_\nu \nabla_x \xi|_{\Sigma \cap U_p} = \sum_{k=1}^{g} \int_{\pi}^{\gamma} \frac{\partial}{\partial x^a} (\xi_p(x_p, u)) dx_p \). We patch \( \iota_\nu \nabla_x \xi|_{\Sigma \cap U_p} \) for each \( p \in \sigma \) to obtain \( \iota_\nu \nabla_x \xi \) which is holomorphic on \( \Sigma \cap U_p \). Let us show that \( \prod_{p=0}^{n} \nabla_{\Sigma \cap U_p} \xi \) is free of \( \xi_p \). Hence \( \iota_\nu \nabla_x \xi \in G_\Sigma \), in other words, \( \nabla_x \xi \in \Gamma(B_{\Sigma \cap U_p} T^* B \otimes G) \), as required.

\[ \Box \]

**Lemma 2.5.27** The vector bundle \( G \rightarrow B_{\Sigma \cap U_p} \) with the connection \( \nabla_x \) is flat.

**Proof:** This is mostly identical to the proof of Lemma 2.4.18, but let us write it more concretely this time. Let \( d\xi : \Gamma(B_{\Sigma \cap U_p} \Omega^2 \otimes G) \rightarrow \Gamma(B_{\Sigma \cap U_p} \Omega^2_\Sigma \otimes G) \) be the exterior covariant derivative. Suppose that \( \xi \in \Gamma(B_{\Sigma \cap U_p} \Omega^2 \otimes G) \). On each \( \Sigma \cap U_p \) we have \( \xi|_{\Sigma \cap U_p} = \sum_{a=1}^{g} \int_{\pi}^{\gamma} (\xi_{i_{1} \cdots i_{p}}(x_p, u)x_p) dx_p \wedge \cdots \wedge dx_{p} \), therefore

\[ d\nabla_x \xi|_{\Sigma \cap U_p} = \sum_{k=1}^{g} \int_{\pi}^{\gamma} \frac{\partial}{\partial x^k} (\xi_{i_{1} \cdots i_{p}}(x_p, u)x_p) dx_p \wedge \cdots \wedge dx_{p} \]

and

\[ d\nabla_x \xi|_{\Sigma \cap U_p} = \sum_{k=1}^{g} \int_{\pi}^{\gamma} \frac{\partial^2}{\partial x^k \partial u} (\xi_{i_{1} \cdots i_{p}}(x_p, u)x_p) dx_p \wedge \cdots \wedge dx_{p} = 0. \]

Therefore, \( d\nabla_x \xi = 0 \), so \( \nabla_x \) is flat. \( \Box \)

Next, we turn our attention to the parallel transport on \( G \) using the connection \( \nabla_x \). Since the connection is flat, parallel transport is path-independent. The parallel transport of \( \xi \in G_{\Sigma} \) to the fiber \( G_{\Sigma} \) only exists if \( \Sigma \in B \). This is much like the situation in Section 2.4 given \( \xi \in W_{\nu}^{\Sigma} \) then \( \exp(a L_{\Sigma} \nu) \xi \in W_{\nu}^{\Sigma} \) only if \( |a| \) is sufficiently small. The idea is to first construct a map \( s_{\Sigma, \Sigma} \) sending points on \( \Sigma_{\nu} \) to \( \Sigma \) along the foliation leaves, then the parallel transport of \( \xi \in G_{\Sigma} \) to \( G_{\Sigma} \) is given by the pull-back \( s_{\Sigma, \Sigma} \).

Let us discuss this in more detail. Suppose that \( \Sigma, \Sigma_{\nu} \in B_{\Sigma} \), then they are path-connected since \( B_{\Sigma} \) is contractible as required by (2.5.2). Let \( \Sigma : [0, 1] \rightarrow B_{\Sigma} \) be such a path, \( \Sigma(0) = \Sigma_{\nu} \), and \( \Sigma(1) = \Sigma \). For some \( \epsilon_{\nu} < \epsilon_{\alpha} \), let us send a point \( q_{\nu} \in \Sigma_{\nu} \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \) traveling along a leaf of the foliation \( F \). If \( [\Sigma_{\nu}] \) is sufficiently close to \( \Sigma(t) \in B_{\Sigma} \) for any \( t \in [0, 1] \), then the point \( q_{\nu} \) will intersect \( \Sigma(t) \), potentially multiple times. As we move continuously along the path \( \Sigma \), these intersection points will also move continuously in \( S \). Therefore, for all \( t \in [0, 1] \) sufficiently small, we can define \( q(t) \in \Sigma(t) \) to be the intersection point which moves continuously from \( q(0) = q_{\nu} \). Now, suppose that \( [\Sigma_{\nu}], [\Sigma] \) and every points along the path \( \Sigma \) are sufficiently close to \( [\Sigma_{\nu}] \), then we define the following map

**Definition 2.5.28** The map \( s_{\Sigma, \Sigma} : \Sigma_{\nu} \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \rightarrow \Sigma \) is given by sending any point \( q_{\nu} \in \Sigma_{\nu} \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \) a leaf of the foliation to \( q(1) \in \Sigma \).

**Remark 2.5.29** Technically, the map \( s_{\Sigma, \Sigma} \) should be denoted by \( s_{\Sigma, \Sigma, \epsilon_{\nu}} \) since the set of parameters \( \{\epsilon_{\nu} \in \text{Ram} \} \) is a part of the definition. We are going to stick with the notation \( s_{\Sigma, \Sigma} \) for simplicity, keeping in mind that \( s_{\Sigma, \Sigma} \) is defined on some open subset in \( \Sigma_{\nu} \) containing \( \Sigma_{\nu} \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \).

Suppose further that \( [\Sigma], [\Sigma_{\nu}] \in B_{\Sigma} \), are sufficiently close such that the image of \( s_{\Sigma, \Sigma} \) is contained in \( \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \) for some \( \epsilon_{\alpha} < \epsilon_{\alpha} \). Then given any holomorphic differential form \( \xi \in \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \), the pull-back \( s_{\Sigma, \Sigma}^{*} \xi \) is a holomorphic differential form on \( \Sigma_{\nu} \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma_{\nu}) \). The following lemma gives a more concrete sufficient condition for \( [\Sigma_{\nu}], [\Sigma] \in B \) to be considered ‘sufficiently close’ and shows that if \( \xi \in G_{\Sigma} \) then \( s_{\Sigma, \Sigma}^{*} \xi \in G_{\Sigma_{\nu}} \).

**Lemma 2.5.30** Let \( [\Sigma_{\nu}], [\Sigma] \in B \). Given \( \xi \in G_{\Sigma} \), where \( \xi \) is holomorphic on \( \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma) \) for some \( \epsilon_{\alpha} < \epsilon_{\alpha} \), \forall \alpha \in \text{Ram} \). If we could cover \( \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma) \) with a collection of \( (F, \Omega_{\Sigma}) \)-charts \( U = \{U_{\sigma} \times \mathbb{R} \: \sigma \in \Phi \} \) such that \( \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma) \subset \cup_{\sigma} \Sigma \cap U_{\sigma} \subset \Sigma \setminus \cup_{\alpha \in \text{Ram}} \bar{B}_{\alpha, \epsilon_{\alpha}}(\Sigma) \) and the following properties are satisfied:

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1. For each $p \in \sigma, \Sigma \cap U_p$ is bi-holomorphic to a simply-connected open subset of $\mathbb{C}$ with $x_p$ as a local coordinate.

2. Any $q' \in U_p$ is path-connected in $U_p$ via a leaf of the foliation $F$ to a unique point $q$ on $\Sigma \cap U_p$.

3. For each $p \in \sigma$, $\Sigma' \cap U_p$ is bi-holomorphic to a simply-connected open subset of $\mathbb{C}$ with $x_p$ as a local coordinate and $\Sigma' \setminus \cup_{a \in \text{Ram}} B_{a, \epsilon_a} (\Sigma') \subset \cup_{p \in \sigma} \Sigma' \cap U_p$.

then $s_{\Sigma', \Sigma}^* \xi \in G_{\Sigma'}$.

**Proof:** Let $\xi \in G_{\Sigma}$ be a holomorphic form on $\Sigma' \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma)$ for some $\epsilon_a < \epsilon_0$ such that $\cup_{a \in \sigma} \Sigma \cap U_p \subset \Sigma \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma)$. By the properties of the covering $U$, Definition 2.5.28 gives a well-defined map $s_{\Sigma', \Sigma} : \Sigma' \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma') \subset \cup_{p \in \sigma} \Sigma' \cap U_p \rightarrow \cup_{p \in \sigma} \Sigma \cap U_p \subset \Sigma \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma)$ for some $\epsilon_a < \epsilon_0$. Let us verify that the pull-back $s_{\Sigma', \Sigma}^* \xi$ is in $G_{\Sigma'}$. We note that $x_p$ is a local coordinate for both $\Sigma \cap U_p$ and $\Sigma' \cap U_p$. In $x_p$ coordinate, we can express $s_{\Sigma', \Sigma}^* \xi$ as

$$x_p \circ s_{\Sigma', \Sigma}[\Sigma' \cap U_p] \circ x_p^{-1} = id_{C} \circ x_p (\Sigma' \cap U_p) : x_p (\Sigma' \cap U_p) \rightarrow x_p (\Sigma' \cap U_p) \subset x_p (\Sigma \cap U_p) \subset \mathbb{C}.$$  

In particular, $s_{\Sigma', \Sigma}^* \xi$ is locally bi-holomorphic from each $\Sigma' \cap U_p$ to its image. It follows that $s_{\Sigma', \Sigma}^* \xi \in G_{\Sigma'}$.

Lastly, we need to check that $\xi \in G_{\Sigma}$ as an element $\xi$, but this follows from the lemma below:

**Lemma 2.5.31** For any $\xi \in G_{\Sigma}$ holomorphic on $\Sigma \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma) \subset \cup_{p \in \sigma} \Sigma \cap U_p$ and a path $C \subset \Sigma' \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma)$, we have

$$\int_{C} s_{\Sigma', \Sigma}^* \xi = \int_{(s_{\Sigma', \Sigma})_{*} C} \xi,$$

where $(s_{\Sigma', \Sigma})_{*} C \subset \Sigma \setminus \cup_{a \in \text{Ram}} \bar{B}_{a, \epsilon_a} (\Sigma)$ is the image of $C$ under the map $s_{\Sigma', \Sigma}$.

**Proof:** We dissect $C$ into closed segments $C_i, i = 1, ..., N$ such that $C_i \subset \Sigma \cap U_{p_i}$ for some $p_i \in \sigma$. As we have seen, $s_{\Sigma', \Sigma} \xi \mid_{\cup_{p \in \sigma} \Sigma \cap U_p}$ is a restriction of the identity, hence it is biholomorphic. So the Lemma holds for each segment $C_i$. Summing the integral over all segments $C_i$ proving the lemma.

It follows from the construction of the map $s_{\Sigma', \Sigma}$ that $(s_{\Sigma', \Sigma})_{*} (\partial \bar{B}_{a, \epsilon_a} (\Sigma'))$ is homotopic to $\partial \bar{B}_{a, \epsilon_a} (\Sigma)$ because we can deform one to another by moving along a path $\Sigma$ linking $[\Sigma]$ and $[\Sigma']$. We conclude that $\xi \in G_{\Sigma}$ as claimed.

Next, we show that the pull-back via $s_{\Sigma', \Sigma}^*$ is the parallel transport on $G$. If Lemma 2.5.30 can be compared to Lemma 2.4.9 then the following is analogous to Lemma 2.4.13.

**Lemma 2.5.32** Let $[\Sigma] \in B_{\Sigma}$ and $\xi \in G_{\Sigma}$ be given, then $[\Sigma'] \mapsto \xi_{\Sigma'} := s_{\Sigma', \Sigma}^* \xi$ is a parallel vector field, defined over the subset of all $[\Sigma'] \in B_{\Sigma}$ such that the conditions of Lemma 2.5.30 are satisfied. In other words, $\xi_{\Sigma'} \in G_{\Sigma'}$ is the parallel transport of $\xi \in G_{\Sigma}$ from $[\Sigma]$ to $[\Sigma']$ on $G \rightarrow B_{\Sigma}$ using the connection $\nabla_F$.

**Proof:** Since $x_p$ is a local coordinate of $\Sigma$ on $\Sigma \cap U_p$ we can write $\xi \mid_{\Sigma \cap U_p} = f(x_p) dx_p$ for some holomorphic function $f$ which is constant with respect to the coordinates of $B_{\Sigma}$. Because $s_{\Sigma', \Sigma} \circ x_p = x_p$ by definition, we have $s_{\Sigma', \Sigma}^* \xi \mid_{\Sigma' \cap U_p} = f(x_p) dx_p$. Therefore, $\nabla_F s_{\Sigma', \Sigma}^* \xi \mid_{\Sigma' \cap U_p} = 0$ for all $p \in \sigma$ and so $\nabla_F s_{\Sigma', \Sigma}^* \xi = 0$.

Now that all the relevant results have been established, let us assume that $\{\epsilon_a \in \text{Ram}\}, \{M_a \in \text{Ram}\}, U_{\text{Ram}}$ and $B_{\Sigma}$ also satisfy 2.5.23 and 2.5.24 in addition to 2.5.21 and 2.5.22. Let us show in the following that the image of $B_{\Sigma}$ under $\gamma$ defined in 2.53 is contained in $\text{Discs}_{\text{Ram}}^{\text{Ram}}$. This fact will be useful in comparing parallel transport on $W_{\text{Ram}} \rightarrow \text{Discs}_{\text{Ram}}^{\text{Ram}}$ with parallel transport on $G \rightarrow B_{\Sigma}$.

**Lemma 2.5.33** Suppose that $\{\epsilon_a \in \text{Ram}\}, \{M_a \in \text{Ram}\}, U_{\text{Ram}}$ and $B_{\Sigma}$ satisfies the Condition 2.5.3 then the image of $\gamma : B_{\Sigma} \rightarrow \text{Discs}_{\text{Ram}}^{\text{Ram}}$ is contained in $\text{Discs}_{\text{Ram}}^{\text{Ram}}$. In other words, we have

$$\gamma : B_{\Sigma} \hookrightarrow \text{Discs}_{\text{Ram}}^{\text{Ram}} \hookrightarrow \text{Discs}_{\text{Ram}}^{\text{Ram}}.$$  

(2.66)
Proof: 2.5.21 and 2.5.22 ensure that the map \( \gamma : \mathcal{B}_{\Sigma_0} \to \text{Discs}^{\text{Ram}} \) is well-defined. We are going to show that 2.5.23 implies that if \( \sum_{k=0}^{\infty} b_k(\Sigma) \cdot z_\alpha^k \) has a radius of convergence \( M_\alpha \), then \( \min(M_\alpha^2 - M_\alpha^2, \epsilon_\alpha^2) > |a_\alpha(\Sigma) - a_\alpha(\Sigma_0)| \) for all \( [\Sigma] \in \mathcal{B}_{\Sigma_0} \).

It is well-known that there is no point on a compact Riemann surface where all holomorphic differential forms vanish simultaneously [19]. In particular, for any ramification point, \( r_\alpha, \alpha \in \text{Ram} \) there exists a holomorphic differential form \( \omega \in \Gamma(\Sigma_0, \Omega_{\Sigma_0}) \subset G_{\Sigma_0} \) such that \( \omega(r_\alpha) \neq 0 \). For clarity, let us denote the standard local coordinate on \( \Sigma_0 \cap U_\alpha \) by \( z_\alpha, \Sigma_0 \) and the standard local coordinate on \( \Sigma \cap U_\alpha \) by \( z_\alpha \). Let us write \( i_\alpha(\omega) = \sum_{k=1}^{\infty} \omega_{\alpha,k} \cdot z_\alpha^k \cdot \frac{dz_\alpha}{z_\alpha} \in T_\alpha L_{\text{Airy}} \subset W_{r_\alpha,\Sigma}^{\text{Ram}} \) where \( \sum_{k=1}^{\infty} \omega_{\alpha,k} \cdot z_\alpha^k \) converges for \( |z_\alpha| < M_\alpha \) for some \( M_\alpha > M_\alpha \). Using the fact that \( x_\alpha = a_\alpha(\Sigma) + z_\alpha^2 \) on \( \Sigma \cap U_\alpha \) and \( x_\alpha = a_\alpha(\Sigma_0) + z_\alpha^2 \) on \( \Sigma_0 \cap U_\alpha \), it follows that

\[
\omega(z_\alpha, \Sigma_0) - a_\alpha(\Sigma_0)) = \sum_{k=1}^{\infty} \omega_{\alpha,k} \left( \sqrt{x_\alpha - a_\alpha(\Sigma_0)} \right)^{k-1} \, dx_\alpha - a_\alpha(\Sigma_0)
\]

implies

\[
s_{\Sigma, \Sigma_0}(z_\alpha)|_{A_{\alpha}, \Sigma_0}(\Sigma_0) = \sum_{k=1}^{\infty} \omega_{\alpha,k} \left( \sqrt{z_\alpha^2 + a_\alpha(\Sigma) - a_\alpha(\Sigma_0)} \right)^{k-1} \, dz_\alpha - a_\alpha(\Sigma_0).
\]

(2.67)

By 2.5.23 we have that \( s_{\Sigma, \Sigma_0} \omega(z_\alpha) \) is holomorphic on \( A_{\alpha}, \Sigma_0, M_\alpha(\Sigma) \). For the expression in (2.67) to be holomorphic on \( A_{\alpha}, \Sigma_0, M_\alpha(\Sigma) \) we must have \( M_\alpha^2 > M_\alpha^2 + |a_\alpha(\Sigma) - a_\alpha(\Sigma_0)| \) and either \( c_\alpha^2 > |a_\alpha(\Sigma) - a_\alpha(\Sigma_0)| \) or that \( \omega_{\alpha,k} = 0 \) for all \( k \) odd and all \( \alpha \in \text{Ram} \). But the latter option is not possible since \( \omega(r_\alpha) \neq 0 \).

\[ \square \]

2.5.6 Comparison of vector bundles \( G \to \mathcal{B}_{\Sigma_0}, \mathcal{H} \to \mathcal{B}, \) and \( W^{\text{Ram}} \to \text{Discs}^{\text{Ram}} \)

So far we have introduced covariantly constant flat (weak) symplectic vector bundles \( (H \to B, \Omega_{\mathcal{B}}, \nabla_{GM}) \), \( (W^{\text{Ram}} \to \text{Discs}^{\text{Ram}}, \Omega, \nabla), \) and a flat coisotropic vector bundle \( (G \to \mathcal{B}_{\Sigma_0}, \nabla_{x}) \). We are now in a position to summarize how they are related.

Proposition 2.5.34 The morphisms of vector bundles \( [\cdot] : G \to \mathcal{H} \) given by taking the cohomology class and \( i : G \to W^{\text{Ram}} \) given by Laurent series expansions are compatible with the connections in the sense that

1. \( i(\nabla_{x}\xi) = \gamma^{*} \nabla_{i}(\xi) \)
2. \( [\nabla_{x}\xi] = \nabla_{GM}[\xi] \)

for any sections \( \xi \in \Gamma(\mathcal{B}_{\Sigma_0}, G) \). Moreover, they are compatible with parallel transport in the sense that

3. \( i(s^{\ast}_{\Sigma_0, \Sigma} \xi_{\Sigma}) = \sum_{[\alpha] \in \text{Ram}} [\alpha] \otimes \exp\left( (a(\Sigma') - a(\Sigma)) L_{\frac{1}{2z_\alpha}} \right) i_{\alpha}(\xi_{\Sigma}) \)
4. \( [s^{\ast}_{\Sigma_0, \Sigma} \xi_{\Sigma}] = \Gamma(\Sigma')_{[\xi]} \)

for any vectors in the fiber \( \xi_{\Sigma} \in G_{\Sigma} \) given that \([\Sigma], [\Sigma'] \in \mathcal{B}_{\Sigma_0} \) and \( \xi_{\Sigma} \) satisfies the conditions of Lemma 2.5.30.

Proof:

1. Let \( \xi \in \Gamma(\mathcal{B}_{\Sigma_0}, G) \) and let us examine \( \nabla_{x}\xi \) on \( \Sigma \cap U_\alpha \subset \Sigma \). Working in the standard local coordinates we can write \( \xi_{\alpha} = \xi_{\alpha}(z_\alpha, u) \cdot dz_\alpha \). Using the fact that \( x_\alpha = a_\alpha(\Sigma) + z_\alpha^2 \), we have \( \frac{\partial x_\alpha}{\partial u^k} |_{z_\alpha=\text{const}} = - \frac{1}{2z_\alpha} \frac{\partial a_\alpha(\Sigma)}{\partial u^k} \) and so

\[
i_{\alpha}(\nabla_{x}\xi_{\alpha})(z_\alpha) = i_{\alpha} \left( \sum_{k=1}^{\infty} du^k \left( \left. \frac{\partial}{\partial u^k} \right|_{z_\alpha=\text{const}} \xi_{\alpha} - \frac{1}{2z_\alpha} \frac{\partial a_\alpha(\Sigma)}{\partial u^k} \xi_{\alpha} \right) \right) dz_\alpha + \xi_{\alpha} \cdot \left( \frac{1}{2z_\alpha} \frac{\partial a_\alpha(\Sigma)}{\partial u^k} \right)
\]

for every \( \alpha \in \text{Ram} \). It follows that \( i(\nabla_{x}\xi) = \gamma^{*} \nabla_{i}(\xi) \) as claimed.

2. This immediately follows from Lemma 2.1.17 with \( D_{\Sigma} := \Sigma \setminus \cup_{p \in \partial} \partial_{\alpha, \epsilon, \alpha}(\Sigma) \) for some \( \epsilon_\alpha < \epsilon_\alpha, \alpha \in \text{Ram} \).
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3. Let $\xi_\Sigma \in G_\Sigma$ and let us write $\xi_\Sigma$ on $\Sigma \cap U_\alpha \subset \Sigma$ in the standard local coordinates as $\xi_\Sigma = \xi_\alpha(z_\alpha)dz_\alpha$. Recall that the local coordinates of $S$ on $U_\alpha$ are $(x_\alpha, y_\alpha)$ and the foliation $F$ is given by $x_\alpha = \text{const}$, so we have $s^*_{\Sigma^\prime, \Sigma}x_\alpha = x_\alpha$. For clarity, let us denote the standard local coordinate on $\Sigma' \cap U_\alpha$ by $z_\alpha^2$ whereas $z_\alpha$ denotes the standard local coordinate on $\Sigma \cap U_\alpha$. Using the fact that $x_\alpha = a_\alpha(\Sigma') + z_\alpha^2$ on $\Sigma \cap U_\alpha$ and $x_\alpha = a_\alpha(\Sigma)$, we have

$$\xi_\Sigma(z_\alpha) = \xi_\alpha(z_\alpha)dz_\alpha = \xi_\alpha \left( \sqrt{x_\alpha - a_\alpha(\Sigma)} \right) d\sqrt{x_\alpha - a_\alpha(\Sigma)}$$

and

$$s^*_{\Sigma^\prime, \Sigma} \xi_\Sigma(z_\alpha) = \xi_\alpha \left( \sqrt{x_\alpha - a_\alpha(\Sigma)} \right) d\sqrt{x_\alpha - a_\alpha(\Sigma)} = \xi_\alpha \left( \sqrt{z_\alpha^2 + a_\alpha(\Sigma') - a_\alpha(\Sigma)} \right) d\sqrt{z_\alpha^2 + a_\alpha(\Sigma') - a_\alpha(\Sigma)} = \exp \left( (a_\alpha(\Sigma') - a_\alpha(\Sigma))L_{\sqrt{x_\alpha - a_\alpha(\Sigma)}} \right) (\xi)$$

By construction, $s^*_{\Sigma^\prime, \Sigma} \xi_\Sigma$ is holomorphic and it can be represented by a Laurent series converging on $\mathbb{B}_{\alpha, \epsilon, \bar{M}, \bar{M}}(\Sigma')$ for some $\epsilon_\alpha < \epsilon < M_\alpha - M_\alpha$. Repeating the above for each ramification point $\alpha \in \text{Ram}$ and perform a Laurent series expansion, the claimed formula follows.

4. Since $(s_{\Sigma, \Sigma'}) : H_1(\Sigma', \mathbb{C}) \rightarrow H_1(\Sigma, \mathbb{C})$ is an isomorphism, mapping $A, B$-periods on $\Sigma'$ to $A, B$-periods on $\Sigma$, then $[s^*_{\Sigma^\prime, \Sigma}] = \Gamma(\Sigma)_{[\xi]}$ follows straightforwardly from Lemma 2.5.31.

\[\square\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_1.png}
\caption{Comparison of vector bundles $G \rightarrow B_{\Sigma_0}$, $\mathcal{H} \rightarrow B$, and $W_{\text{Ram}} \rightarrow \text{Discs}_{\text{Ram}}$. The vector bundle morphism $[\cdot] : G \rightarrow \mathcal{H}$ covering the inclusion map $B_{\Sigma_0} \hookrightarrow B$ is given fiber-wise by the natural projection $G_\Sigma \rightarrow G_\Sigma/G^{\Sigma}_0 \cong \mathcal{H}_\Sigma$, which is the same as taking a cohomology class. The vector bundle morphism $i : G \rightarrow W_{\text{Ram}}$ covering the map $\gamma : B_{\Sigma_0} \hookrightarrow \text{Discs}_{\text{Ram}}$ is given by taking Laurent expansions around ramification points. In this sense, the vector bundle $G$ bridges the local point of view given by $W_{\text{Ram}}$ with the global point of view given by $\mathcal{H}$. This Figure also illustrates the parallel construction of the map $\Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow \mathcal{H}_{\Sigma_0}$, $\Phi_{\Sigma} : B_{\Sigma} \rightarrow G_{\Sigma}$, and $\Phi_{t_0} : \text{Discs}_{\text{Ram}} \rightarrow W_{\text{Ram}}$. Each map embeds some neighbourhood $B_{\Sigma_0} \ni [\Sigma_0]$ or $\text{Discs}_{\text{Ram}} \ni t_0$ into the fiber $\mathcal{H}_{\Sigma_0}$, $G_{\Sigma_0}$ or $W_{\text{Ram}}$ over the reference point by sending the zero vector at an arbitrary point to the reference point via parallel transport using the affine connection $\nabla_{GM} + \Phi, \nabla_{F} + \phi$ or $\nabla + \phi$.}
\end{figure}

2.5.7 The embedding of $B_{\Sigma_0}$ into $G_{\Sigma_0}$ and the residue constraints

In this section, we will construct the embedding map $\Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow G_{\Sigma_0}$ analogous to $\Phi_{\Sigma} : B_{\Sigma} \rightarrow \mathcal{H}_{\Sigma_0}$ defined in Section 2.1.3 and $\Phi_{t_0} : \text{Discs}_{\text{Ram}}^M \rightarrow W_{\text{Ram}}^M$ defined in Section 2.4.3. The main outcome of this section is Proposition 2.5.38 comparing $\Phi_{\Sigma_0}$ to $\Phi_{t_0}$ and $\Phi_{\Sigma}$, which is the key result to be used in proving Theorem 2.7.3 later. To construct $\Phi_{\Sigma_0}$, we are going to need $\phi \in \Gamma(B_{\Sigma_0}, T^*B \otimes G)$ and find $\theta \in \Gamma(B_{\Sigma_0}, G)$ such that $\nabla_F \theta = \phi$. 

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Therefore, most of this section leading up to Proposition 2.5.3 will be allocated to discuss the construction and properties of $\phi$ and $\theta$. We are also going to assume $\{t_\alpha \in \Ram\}, \{M_\alpha \in \Ram\}, \U$ and $\mathcal{B}_\Sigma$ are chosen such that Condition 2.5.2 is satisfied.

Let us begin by discussing $\phi \in \Gamma(\mathcal{B}_\Sigma, T^* \mathcal{B} \otimes G)$ as follows. At any point $[\Sigma] \in \mathcal{B}_\Sigma$, the map $\phi_\Sigma : T[\Sigma] \mathcal{B}_\Sigma \xrightarrow{\sim} \Gamma(\Sigma, \Omega_2^n)$ has already been defined previously in Section 2.1 but let us recall it here. Any given vector $v \in T[\Sigma] \mathcal{B}_\Sigma$ can be mapped into a global holomorphic section of normal bundle $n_v \in \Gamma(\Sigma, \nu_\Sigma)$. Then $\phi_\Sigma(v) := \Omega_2(n_v, \cdot)_\Sigma \in \Gamma(\Sigma, \Omega_2^n)$. Let us cover $\Sigma$ with a collection of $(\mathcal{F}, \Omega_2^n)$-charts $\mathcal{U} = \{(U_p \in \sigma, x_p \in \sigma, y_p \in \sigma)\}$ then $\phi_\Sigma(v)$ is written locally on each $\Sigma \cap U_p$ as

$$\phi_\Sigma(v)|_{\Sigma \cap U_p} = -t_v \nabla x_p(y_pdx_p)|_{\Sigma \cap U_p}. \quad (2.68)$$

Now, let us compare this to $\phi \in \Gamma(\mathcal{B}_\Sigma, T^* \mathcal{B} \otimes H)$ from Section 2.1.2 and

$$\phi := \sum_{\alpha \in \Ram} [\alpha] \otimes \phi_\alpha \in \Gamma(\Discs_{\alpha}^{\Ram}, \Hom(\Discs_{\alpha}^{\Ram}, W^{\Ram})),$$

where $\phi_\alpha \in \Gamma(\Discs_{\alpha}^{\Ram}, \Hom(\Discs_{\alpha}^{\Ram}, W^{\Ram}))$ are as given in Section 2.4. For example, let $t = (t_\alpha \in \Ram) \in \Discs_{\alpha}^{\Ram}, t_\alpha \in \Discs_{\alpha}^{\Ram}$ and $v = (v_\alpha \in \Ram) \in T_t \Discs_{\alpha}^{\Ram}, v_\alpha \in T_t \Discs_{\alpha}^{\Ram}$, we define $\phi_t(v) := \sum_{\alpha \in \Ram}[\alpha] \otimes \phi_\alpha(v_\alpha)$. We have the following lemma compare $\phi_\Sigma$ to $\phi_{(\Sigma)}$ and $\phi_{\Sigma}$:

**Lemma 2.5.35** Let $\phi \in \Gamma(\mathcal{B}_\Sigma, T^* \mathcal{B} \otimes H)$ be given as above, then

1. $\{\phi_\Sigma\} = \Phi_{\Sigma}$
2. $i(\phi_{\Sigma}) = \phi_{(\Sigma)} \circ d\gamma$.

**We summarize these relationships by the following commutative diagram**

\[
\begin{array}{ccc}
G_{\Sigma}/G_{\Sigma}^1 & \xrightarrow{i} & W_{\Ram}^{\Airy} \\
\downarrow \cong & & \downarrow \cong \\
\mathcal{H}_{\Sigma} & \xrightarrow{\phi_{\Sigma}} & \Gamma(\Sigma, \Omega_2^n) \\
\uparrow \cong & & \uparrow \cong \\
T[\Sigma] \mathcal{B}_\Sigma & \xrightarrow{d\gamma} & T(\Sigma) \Discs_{\alpha}^{\Ram}
\end{array}
\]

**Proof:**

1. This is obvious since $\phi_{\Sigma} = \sum_{k=1}^{\alpha}[\Omega_2(n_{v_k}, \cdot)|_{\Sigma}]d^k$ by definition.
2. Given $t_\alpha \in \Discs_{\alpha}^{\Ram}, t_\alpha = (x_\alpha = z^2 + a_\alpha, y_\alpha = \sum_{k=0}^{\infty} b_{ka,z^k})$ and vector $v_\alpha = A_\alpha \frac{\partial y_\alpha}{\partial a_\alpha} + \sum_{k=0}^{\infty} B_{ka} \frac{\partial y_\alpha}{\partial b_{ka}} \in T_t \Discs_{\alpha}^{\Ram}$ we can also compute $\phi_{\alpha, t_\alpha}$ defined in Section 2.4 by keeping $x_\alpha = \text{const}$ when taking derivatives and use $\frac{\partial y_\alpha}{\partial a_\alpha}|_{x_\alpha = \text{const}} = -\frac{1}{2a_\alpha}$. We have

$$\phi_{\alpha, t_\alpha}(v_\alpha) = \Omega_2 \left( A_\alpha \frac{\partial y_\alpha}{\partial a_\alpha}|_{x_\alpha = \text{const}} + \sum_{k=0}^{\infty} B_{ka} \frac{\partial y_\alpha}{\partial b_{ka}}|_{x_\alpha = \text{const}} \right) \frac{\partial}{\partial y_\alpha},$$

which should be compared to (2.51). Setting $t_\alpha = t_\alpha(\Sigma) = \gamma_\alpha(\Sigma)$ and

$$v_\alpha = d\gamma(v_\alpha) = \sum_{k=1}^{\alpha} v^k \left( \frac{\partial a_\alpha(\Sigma)}{\partial u^k} \frac{\partial}{\partial a_\alpha} + \sum_{l=0}^{\infty} \frac{\partial b_{ka}(\Sigma)}{\partial u^k} \frac{\partial}{\partial b_{ka}} \right)$$

shows that $i_\alpha \phi_{\Sigma} = \gamma_\alpha^* \phi_{\alpha} = \phi_{\alpha} \circ d\gamma_\alpha$. 

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Since $\mathcal{B}_{\Sigma_0}$ is chosen to be contractible (2.5.2.1), $G \to \mathcal{B}_{\Sigma_0}$ is a flat vector bundle and $d_{\nabla} \phi = 0$, therefore Poincaré Lemma suggests the existence of $\theta \in \Gamma(\mathcal{B}_{\Sigma_0}, G)$ such that $\nabla_{\xi} \theta = \phi$. $\theta_\Sigma$ is a holomorphic differential form on $\Sigma \setminus \cup_{\alpha \in \mathcal{R}am} \mathcal{B}_{\alpha, \epsilon_\alpha} = \Sigma$ for some $\epsilon_\alpha < \epsilon_\alpha$. $f_{\mathcal{B}_{\alpha, \epsilon_\alpha}} \theta_\Sigma = 0$ and any infinitesimal variation of $\theta_\Sigma$ in the moduli space directions produce a global holomorphic form on $\Sigma$, i.e., a holomorphic form on $\Sigma \setminus \cup_{\alpha \in \mathcal{R}am} \mathcal{B}_{\alpha, \epsilon_\alpha} = \Sigma$ which can be analytically extended to the entire curve $\Sigma$.

**Lemma 2.5.36** Let $\theta \in \Gamma(\mathcal{B}_{\Sigma_0}, G)$ be a section satisfying $\nabla_{\xi} \theta = \phi$, then

1. $[\theta_\Sigma] = \theta_{\Sigma} + \Gamma^{\Sigma}_{\Sigma_0}[\xi_0] \in \mathcal{H}_{\Sigma}$ for some $[\xi_0] \in \mathcal{H}_{\Sigma_0}$.

2. $i(\theta_{\Sigma}) = \sum_{\alpha \in \mathcal{R}am} [\theta_{\alpha}(\Sigma)] \otimes \left( \theta_{\alpha}(\Sigma) + \exp \left( \left( a_{\alpha}(\Sigma) - a_{\alpha}(\Sigma_0) \right) \right) \right) \in W^{Ram}_{\alpha, M_0}$ for some $\xi_{\alpha} \in W^{\epsilon_0, M_0}$ where

$$
\epsilon_\alpha := \sqrt{\epsilon_0^2 - \sup_{[\xi] \in \mathcal{B}_{\Sigma_0}} |a_{\alpha}(\Sigma) - a_{\alpha}(\Sigma_0)|}, \quad M_\alpha := \sqrt{M_0^2 + \sup_{[\xi] \in \mathcal{B}_{\Sigma_0}} |a_{\alpha}(\Sigma) - a_{\alpha}(\Sigma_0)|}.
$$

where $\theta_{\Sigma} \in \mathcal{H}_{\Sigma}$ is given by (2.14) and $\theta_{\alpha}(\Sigma) \in W^{\epsilon_0, M_0}$ is given by (2.52).

**Proof:**

1. By taking cohomology class, apply Proposition 2.5.34 and Lemma 2.5.35, we find that $\nabla_{\xi} \theta_{\Sigma} = \phi_{\Sigma} = \phi_{\Sigma}$. Therefore, we have $|\theta| = \theta + c$ for some parallel section $c \in \Gamma(\mathcal{B}_{\Sigma_0}, \mathcal{H})$, $\nabla_{\xi} c = 0$. But then we can write $c_\Sigma = \Gamma^{\Sigma}_{\Sigma_0}[\xi_0]$ where $[\xi_0] := c_\Sigma \in \mathcal{H}_{\Sigma_0}$.

2. By applying the map $i : G : \Gamma^{\Sigma}_{\Sigma_0}(\Sigma, \mathcal{H})$ follows by Proposition 2.5.34 and Lemma 2.5.35 we have $\gamma^{\ast} \nabla_{\xi} \theta_{\Sigma} = i(\nabla_{\xi} \theta_{\Sigma}) = i(\phi_{\Sigma}) = \partial_{\alpha}(\Sigma) \otimes d \gamma$. Therefore, we have $i(\theta_{\Sigma}) = \sum_{\alpha \in \mathcal{R}am} [\alpha] \otimes \theta_{\alpha}(\Sigma) + c$ for some parallel section $c \in \Gamma(\mathcal{B}_{\Sigma_0}, \mathcal{H})$, $\nabla_{\xi} c = 0$. It is not hard to check that

$$
eq \sum_{\alpha \in \mathcal{R}am} [\alpha] \otimes \exp \left( \left( a_{\alpha}(\Sigma) - a_{\alpha}(\Sigma_0) \right) \right) \xi_{\alpha}$$

where $\sum_{\alpha \in \mathcal{R}am} [\alpha] \otimes \xi_{\alpha} = c_\Sigma \in W^{Ram}_{\alpha, M_0}$.

Let us show explicitly how $\theta \in \Gamma(\mathcal{B}_{\Sigma_0}, G)$ such that $\nabla_{\xi} \theta = \phi$ can be constructed. In the case of $(\mathcal{F}, \Omega_{\Sigma})$-charts $U_0 = \{ x_{p \in \sigma_0}, \sigma_{p \in \sigma_0}, y_{p \in \sigma_0} \}$ which allows the parallel transport of any holomorphic form $\xi \in \Omega_{\Sigma_0, \Omega_{\Sigma_0}} \subset \mathcal{G}_{\Sigma_0}$ to $G_{\Sigma_0}$ for any $[\xi_0] \in \mathcal{B}_{\Sigma_0}$ according to Lemma 2.5.32. Such a collection $U_0$ exists due to (2.5.2.4). From (2.5.8) we know that $\theta_{\Sigma}|_{\Sigma \cap U_{\alpha, p}}$ must take the form $- (y_p + F_p(x_p)) d x_p |_{\Sigma \cap U_{\alpha, p}}$ for us to have $\nabla_{\xi} \Sigma|_{\Sigma \cap U_{\alpha, p}} = \phi_{\Sigma}|_{\Sigma \cap U_{\alpha, p}}$, where $f_p(x_p) d x_p$ is an integration constant. Write $y_p(x_p, \Sigma) d x_p := y_p(x_p, \Sigma) |_{\Sigma \cap U_{\alpha, p}}$ for each $p \in \sigma$. In other words, $\Sigma \cap U_{\alpha, p} = \{ (x_p, y_p(x_p, \Sigma)) \} \in U_p \subset S \mid x_p \in x_p \Sigma \cap U_{\alpha, p} \}$ is the graph of $y_p = y_p(x_p, \Sigma)$. Then, on each open subset $\Sigma \cap U_{\alpha, p}$, let us define

$$
\theta_{\Sigma}|_{\Sigma \cap U_{\alpha, p}} := - y_p(x_p, \Sigma) d x_p + y_p(x_p, \Sigma) d x_p.
$$

If each $\theta_{\Sigma}|_{\Sigma \cap U_{\alpha, p}}$ can be patched together to get $\theta_{\Sigma} \in G_{\Sigma}$, then it will automatically follows that $\nabla_{\xi} \theta_{\Sigma} = \phi_{\Sigma}$ as this relation holds on every $\Sigma \cap U_{\alpha, p}$ and we are done. The following guarantees that this is the case:

**Lemma 2.5.37** Each $\theta_{\Sigma}|_{\Sigma \cap U_{\alpha, p}}, p \in \sigma_0$ can be patched together as $\theta_{\Sigma} \in G_{\Sigma}$.

**Proof:** First, let us show that each $\theta_{\Sigma}|_{\Sigma \cap U_{\alpha, p}}$, $p \in \sigma_0$ can be patched together to form a global holomorphic form $\theta_{\Sigma}$ on $\Sigma \setminus \cup_{\alpha \in \mathcal{R}am} \mathcal{B}_{\alpha, \epsilon_\alpha} = \Sigma$ for some $\epsilon_\alpha < \epsilon_\alpha$. Using the coordinates transformation on $U_{p, 0} \cap U_{\alpha, p}$ between $(x_{p, 0}, y_{p, 0})$ and $(x_{p, 0}, y_{p, 0})$ as given in (2.1), we find that $x_{p'} = F_{p'}(x_p)$ and

$$
y_{p'}(x_p, \Sigma) = \frac{y_p(F^{-1}_{p'}(x_p)); \Sigma)}{y_p(F^{-1}_{p'}(x_{p'})); \Sigma)} - G_{p'}(F^{-1}(x_p)), \quad y_{p'}(x_{p'}, \Sigma) = \frac{y_p(F^{-1}_{p'}(x_{p'})); \Sigma)}{y_p(F^{-1}_{p'}(x_{p'})); \Sigma)} - G_{p'}(F^{-1}(x_{p'})).
$$

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This means

\[
\begin{align*}
(\theta_\Sigma|_{\Sigma \cap U_{\alpha,p}})_{|\Sigma \cap U_{\alpha,p} \cap U_{\alpha,p'}} &= -y p' (x p'); \Sigma) dx p' + y p' (x p'; \Sigma_0) dx p' \\
&= -\left( y p' (F p^{-1} (x p'); \Sigma) \right) \frac{F p'}{F p^{-1} (x p')} - G p' (F p^{-1} (x p')) dx p' \\
&= -y p' (x p'; \Sigma) dx p + y p' (x p'; \Sigma_0) dx p \\
&= \left( \theta_\Sigma|_{\Sigma \cap U_{\alpha,p}} \right)_{|\Sigma \cap U_{\alpha,p} \cap U_{\alpha,p'}}.
\end{align*}
\]

Therefore, we can patch together each \( \theta_\Sigma|_{\Sigma \cap U_{\alpha,p}} \) for \( p \in \sigma_0 \) to get a well-defined holomorphic form \( \theta_\Sigma \) on \( \cup_{p \in \sigma_0} \Sigma \cap U_{\alpha,p} \supset \Sigma \setminus \cup_{\alpha \in \text{Ram}} \mathbb{D}_{\alpha,\epsilon_\alpha}(\Sigma) \).

To finish showing that \( \theta_\Sigma \in G_\Sigma \), we need to check that \( \oint_{\partial H_\Sigma} \theta_\Sigma = 0 \). Since \( \theta_\Sigma \) we have so far is well-defined on the annulus \( A_{\alpha,\epsilon_\alpha,M_\alpha}(\Sigma) \), it can be written in the standard local coordinate \( z_\alpha \) of \( \Sigma \cap U_\alpha \) as

\[
i_\alpha \theta_\Sigma(z_\alpha) = -y_\alpha(z_\alpha; \Sigma) dx_\alpha(z_\alpha) + y_\alpha(z_\alpha; \Sigma_0) dx_\alpha(z_\alpha; \Sigma_0).
\]

where the existence of parallel transport satisfies \( \oint_{\partial H_\Sigma} \theta_\Sigma = 0 \). Since \( \theta_\Sigma \) we have so far is well-defined on the annulus \( A_{\alpha,\epsilon_\alpha,M_\alpha}(\Sigma) \), it can be written in the standard local coordinate \( z_\alpha \) of \( \Sigma \cap U_\alpha \) as

\[
i_\alpha \theta_\Sigma(z_\alpha) = -y_\alpha(z_\alpha; \Sigma) dx_\alpha(z_\alpha) + y_\alpha(z_\alpha; \Sigma_0) dx_\alpha(z_\alpha; \Sigma_0).
\]

For clarity, we have denoted by \( z_{\alpha,\Sigma_0} \) the standard local coordinate on \( \Sigma_0 \cap U_\alpha \) which is related to \( z_\alpha \) by \( a_\alpha(\Sigma) + z_\alpha^2 = x_\alpha = a_\alpha(\Sigma_0) + z_{\alpha,\Sigma_0}^2 \). Let us give more explanation to the second equality. By (2.52) we have \( \theta_{\alpha,\Sigma_0}(\Sigma) = -y_\alpha(z_\alpha; \Sigma) dx_\alpha(z_\alpha) \in W_{\alpha,\Sigma_0}^{\epsilon_\alpha,M_\alpha} \) and \( \theta_{\alpha,\Sigma_0}(\Sigma) = -y_\alpha(z_\alpha; \Sigma_0) dx_\alpha(z_\alpha; \Sigma_0,\Sigma_0) \in W_{\alpha,\Sigma_0}^{\epsilon_\alpha,M_\alpha}. \)

In particular,

\[
y_\alpha(z_\alpha; \Sigma_0) dx_\alpha(z_\alpha; \Sigma_0) = \exp \left( a_\alpha(\Sigma) - a_\alpha(\Sigma_0) \right) \frac{\partial}{\partial a_\alpha(\Sigma)} \theta_{\alpha,\Sigma_0}(z_\alpha; \Sigma_0,\Sigma_0) \bigg|_{z_\alpha,\Sigma_0 = z_\alpha}.
\]

Clearly, \( i_\alpha \theta_\Sigma \) contains no \( \frac{dz_\alpha}{\alpha} \) term according to Lemma 2.4.9 and so \( \oint_{\partial H_\Sigma} \theta_\Sigma = 0 \). \( \square \)

Let us embed the neighborhood \( B_{\Sigma_0} \) of \( [\Sigma_0] \in \mathcal{B} \) into the fiber \( G_{\Sigma_0} \) using the same procedure we did to embed \( B_{\Sigma_0} \) into \( H_{\Sigma_0} \) in Section 2.1 and \( G_{\Sigma_0} \) in Section 2.4 but this time with the vector bundle \( (G \to B_{\Sigma_0}, \nabla_F) \). The embedding map \( \Phi_{\Sigma_0} : B_{\Sigma_0} \to G_{\Sigma_0} \) is given by sending the zero vector \( t_0 \in G_\Sigma \) at \( [\Sigma] \in B_{\Sigma_0} \) into \( G_{\Sigma_0} \) at \( [\Sigma_0] \in B_{\Sigma_0} \) via parallel transport using the connection \( \nabla_F + \phi \). Since \( \nabla_F \phi = \phi \), the parallel transport of \( \theta_\Sigma \) from \( [\Sigma] \in B_{\Sigma_0} \) to \( [\Sigma'] \in \mathcal{B} \) using \( \nabla_F + \phi \) is path-independent and it is uniquely given by

\[
v_{\Sigma}(\Sigma') = -\theta_{\Sigma'} + s_{\Sigma',\Sigma}^* \theta_{\Sigma}.
\]

Therefore,

\[
\Phi_{\Sigma_0}(\Sigma) := v_{\Sigma}(\Sigma_0) = -\theta_{\Sigma_0} + s_{\Sigma_0,\Sigma}^* \theta_{\Sigma} \in G_{\Sigma_0},
\]

where the existence of parallel transport \( s_{\Sigma_0,\Sigma}^* \theta_{\Sigma} \in G_{\Sigma_0} \) is due to (2.5.2) as \( \theta_{\Sigma} \) is holomorphic on \( \cup_{p \in \sigma_0} \Sigma \cap U_{\alpha,p} \supset \Sigma \setminus \cup_{\alpha \in \text{Ram}} \mathbb{D}_{\alpha,\epsilon_\alpha}(\Sigma) \).

Given \( t_0 = (t_{0\alpha}) \in \text{Disc}_{\alpha,\text{Ram}} \), let us define the Ram product version of \( \Phi_{t_0} : \text{Disc}_{\alpha,\text{Ram}} \to W_{t_0}^{\epsilon_\alpha,M_\alpha} \) by \( \Phi_{t_0}(t) := \sum_{\alpha \in \text{Ram}} \Phi_{\alpha,\text{Ram}}(t_{\alpha}) \) for any \( t = (t_{\alpha}) \in \text{Disc}_{\alpha,\text{Ram}} \) where \( \Phi_{\alpha} : \text{Disc}_{\alpha,\text{Ram}} \to W_{t_{\alpha}}^{\epsilon_\alpha,M_\alpha} \) is as given in Section 2.4

\[
\Phi_{\alpha,\text{Ram}}(t_{\alpha}) := -\theta_{t_{\alpha}} + \exp((a_{\alpha}(t_{\alpha}) - a_{\alpha}(t_{\alpha})) \frac{\partial}{\partial a_{\alpha}(t_{\alpha}))} \theta_{t_{\alpha}} \in W_{t_{\alpha}}^{\epsilon_\alpha,M_\alpha}.
\]

Finally, we have the following proposition:

**Proposition 2.5.38 (25 Proposition 7.1.2)** The embedding \( \Phi_{\Sigma_0} : B_{\Sigma_0} \to G_{\Sigma_0} \) satisfies \( \Phi_{\Sigma_0}(\Sigma) = \Phi_{\Sigma_0}(\gamma(\Sigma)) = \Phi_{\Sigma_0}(\gamma^2(\Sigma)) \), so (a) and (b) squares in the diagram are commutative. Moreover, if each \( (\mathcal{F}, \Omega_S) \)-charts \( (U_\alpha, x_\alpha, y_\alpha) \) in \( U_{\text{Ram}} \) are chosen such that \( \gamma_0(\Sigma_0) = (x_\alpha = z_\alpha^2, y_\alpha = z_\alpha) \), then \( \Phi_{\Sigma_0} \) factors
through $L_{\text{Airy}}^{\text{Ram}}$ and the triangle (c) is also commutative.

\[
\begin{array}{c}
\mathcal{L}_{\Sigma_0} \xleftarrow{\cong} B_{\Sigma_0} \xrightarrow{i} G_{\Sigma_0} \xrightarrow{\cong} \mathcal{H}_{\Sigma_0} \\
\Phi_{\Sigma_0} \xrightarrow{\cong} \Phi_{\Sigma_0} \xrightarrow{i} G_{\Sigma_0} \xrightarrow{\cong} W_{\text{Airy}}^{\text{Ram}} \\
L_{\text{Airy}}^{\text{Ram}} \xleftarrow{\cong} B_{\Sigma_0} \xrightarrow{\cong} G_{\Sigma_0} \xrightarrow{\cong} W_{\text{Airy}}^{\text{Ram}} \xrightarrow{\cong} \mathcal{H}_{\Sigma_0}
\end{array}
\]

We note that the left-most triangle is merely a restatement of the definition $\mathcal{L}_{\Sigma_0} := \text{im} \Phi_{\Sigma_0} \subset \mathcal{H}_{\Sigma_0}$ as given in Section 2.1.3 and we include it here for completeness.

**Proof:** The proof is mostly an application of Proposition 2.5.34 and Lemma 2.5.36. From Lemma 2.5.36 we know that $[\theta_\Sigma] = \theta_{\Sigma} + \Gamma_{[\Sigma]}[\xi_0]$ for some $[\xi_0] \in \mathcal{H}_{\Sigma_0}$ and

\[
i_\alpha(\theta_\Sigma) = \theta_{t_\alpha}(\Sigma) + \exp \left( (a_\alpha(\Sigma) - a_\alpha(\Sigma_0))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right)(\xi_0)
\]

for some $\xi_0 \in W_{\text{Ram}}^{M_{\alpha}}$. Therefore, we have

\[
[\Phi_{\Sigma_0}(\Sigma)] = -[\theta_\Sigma] + [\mathcal{E}_{\Sigma}^{\Sigma_0,\Sigma}[\theta_\Sigma] = -[\theta_\Sigma] + \Gamma_{[\Sigma]}[\theta_\Sigma]
\]

\[
= -[\theta_{\Sigma_0} + [\xi_0] + \Gamma_{[\Sigma]}[\theta_\Sigma] + \Gamma_{[\Sigma]}[\xi_0] = -\theta_{\Sigma_0} + [\xi_0] + \Gamma_{[\Sigma]}[\theta_\Sigma] + [\xi_0] = -\theta_{\Sigma_0} + \Gamma_{[\Sigma]}[\theta_\Sigma] = \Phi_{\Sigma_0}(\Sigma)
\]

and so (a) is commutative. Similarly,

\[
i(\Phi_{\Sigma_0}(\Sigma)) = -i(\theta_{\Sigma_0}) + i(\mathcal{E}_{\Sigma}^{\Sigma_0,\Sigma}[\theta_\Sigma])
\]

\[
= -i(\theta_{\Sigma_0}) + \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \exp \left( (a_\alpha(\Sigma_0) - a_\alpha(\Sigma))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right)(\theta_{t_\alpha}(\Sigma))
\]

\[
= -\sum_{\alpha \in \text{Ram}} [\alpha] \otimes \left( \theta_{t_\alpha}(\Sigma_0) - \xi_0 \right)
\]

\[
+ \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \exp \left( (a_\alpha(\Sigma_0) - a_\alpha(\Sigma))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right) (\theta_{t_\alpha}(\Sigma) + \exp \left( (a_\alpha(\Sigma) - a_\alpha(\Sigma_0))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right)(\xi_0))
\]

\[
= \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \left( \theta_{t_\alpha}(\Sigma_0) - \xi_0 \right)
\]

\[
+ \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \exp \left( (a_\alpha(\Sigma_0) - a_\alpha(\Sigma))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right) (\theta_{t_\alpha}(\Sigma) + \xi_0)
\]

\[
= \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \left( \theta_{t_\alpha}(\Sigma_0) + \exp \left( (a_\alpha(\Sigma_0) - a_\alpha(\Sigma))L_{\Sigma_0}^{\frac{1}{\partial \alpha}} \right) (\theta_{t_\alpha}(\Sigma))
\]

\[
= \sum_{\alpha \in \text{Ram}} [\alpha] \otimes \Phi_{\alpha.\Sigma_0}(\theta_{t_\alpha}(\Sigma)) = \Phi_{\Sigma_0}(\ell(\Sigma)) = \Phi_{\Sigma_0} \circ \gamma(\Sigma)
\]

and so (b) is commutative. Lastly, if $\gamma_{\alpha}(\Sigma_0) = (x_\alpha = z_\alpha^2, y_\alpha = z_\alpha)$ then it follows from Proposition 2.4.24 that $\text{im} \Phi_{\alpha.\Sigma_0} \subseteq L_{\text{Airy}}$ and therefore $\text{im} \Phi_{\Sigma_0} \subseteq L_{\text{Airy}}^{\text{Ram}}$ which shows that (c) is commutative.

2.6 From Airy Structures to Topological Recursion

As we have mentioned earlier in Section 2.3, the main reason for our interest in the residue constraints Airy structure is due to its connection to topological recursion. This connection is well-known and has been studied in various places such as [4] [1] [25], however we include this review here for completeness.

2.6.1 Review of Topological Recursion

We recall the following basic facts and setup of the original Eynard-Orantin topological recursion [14] [15]. A spectral curve $(\Sigma_0, x, y, B)$ is given by a smooth compact Riemann surface $\Sigma_0$, global functions $x, y : \Sigma_0 \to \mathbb{P}^1$
and a choice of Bergman kernel \( B = B(p, q) \) on \( \Sigma_0 \times \Sigma_0 \). We assume that \( dx(p) \) has simple zeros at a finite number of points \( p \in \{ r_{\alpha \in \text{Ram}} \in \Sigma_0 \} \) called ramification points and that \( y \sim y(r_{\alpha}) + C \sqrt{x - x(r_{\alpha})} \) near each \( r_{\alpha} \) (it follows that \( dy(r_{\alpha}) \neq 0 \)). We equip to each ramification point the involution map \( \sigma_{\alpha} \) defined locally in some neighbourhood of each \( r_{\alpha} \) satisfying \( \sigma_{\alpha}(r_{\alpha}) = r_{\alpha}, \ x \circ \sigma_{\alpha} = x \) and \( d\sigma_{\alpha}|_{r_{\alpha}} = -id : T_{r_{\alpha}} \Sigma_0 \to T_{r_{\alpha}} \Sigma_0 \). We set the initial condition of the recursion to be

\[
\omega_{0,1}(p) := ydx, \quad \omega_{0,2}(p, q) = B(p, q).
\]

For \( g \geq 0, n \geq 3 \) or \( g \geq 1, n \geq 1 \) we compute the multi-differential \( \omega_{g,n} \in \Gamma \left( (\Sigma_0 \setminus \cup_{\alpha \in \text{Ram}} r_{\alpha})^n, (\Omega_{\alpha}^{\Sigma_0})^\otimes n \right) \) using the following recursion formula

\[
\omega_{g,n}(p_1, \ldots, p_n) = \sum_{\alpha \in \text{Ram}} \text{Res}_{p=r_{\alpha}} K(p_1, p) \omega_{g-1,n+1}(p, \sigma_{\alpha}(p), p_2, \ldots, p_n) \]
\[
+ \sum_{\alpha \in \text{Ram}} \sum_{\text{at } I_1} \text{Res}_{p=r_{\alpha}} K(p_1, p) \omega_{g_1,1+\text{tr}_{I}(p_1, p_1) \omega_{g_2,1+\text{tr}_{I}(\sigma_{\alpha}(p), p_2)} \quad (2.69)
\]

where \( \sum^{*} \) indicates that we exclude all terms involving \( \omega_{0,1} \) from the summation. We also define the recursion kernel \( K = K(p_1, p) \) for \( p_1 \in \Sigma \) and \( p \) in the vicinity of a ramification point by

\[
K(p_1, p) := \frac{1}{2} \left[ \frac{f''(p')}{f'(p') \omega_{0,2}(p_1, p')} - \omega_{0,1}(\sigma_{\alpha}(p)) \right].
\]

We note that \( K(p_1, p) \) is a global meromorphic differential on \( \Sigma_0 \) in \( p_1 \) with simple poles at \( p_1 = p, \sigma_{\alpha}(p) \). On the other hand, \( K(p_1, p) \) is only defined as an inverse of differential locally for \( p \) close to \( r_{\alpha} \) with simple poles at \( p = r_{\alpha} \) for any \( \alpha \in \text{Ram} \). The formula \( (2.69) \) expresses \( \omega_{g,n} \) only in terms of \( \omega_{g',n'} \) for \( 2g' - 2 + n' < 2g - 2 + n \)
and therefore the recursion is guaranteed to terminate.

**Remark 2.6.1** It is known that \( \omega_{g,n}(p_1, \ldots, p_n) \) is a meromorphic differential on \( \Sigma_0 \) symmetric in each of its variable \( p_i \) with poles only at ramification points of \( \Sigma_\alpha \) and zero residues \( \oint_{p=r_{\alpha}} \omega_{g,n}(p_1, \ldots, p_n) = 0 \) \( \text{Corollary 4.1} \). Moreover, if we have chosen \( B = B(p, q) \) to be the normalized Bergman kernel, then \( \oint_{p_{i} \in \text{Ram}} \omega_{g,n}(p_1, \ldots, p_n) = 0 \) \( \text{Theorem 4.3} \).

We observe that we have only used local information of \( \omega_{0,1} \) in the vicinity of each \( r_{\alpha} \). This suggests a slight generalization of the original version of topological recursion. We consider a smooth compact Riemann surface \( \Sigma_0 \) equipped with a choice of Bergman kernel \( B = B(p, q) \) and a set of distinct points \( \{ r_{\alpha \in \text{Ram}} \} \) indexed by the set \( \text{Ram} \). We let \( x \) and \( y \) be locally defined functions on some open neighbourhood \( D_\alpha \) of each \( r_{\alpha} \in \Sigma \) such that \( dx(r_{\alpha}) = 0 \) and \( \tau_{\alpha} := \sqrt{x - x(r_{\alpha})} \) is a local coordinate on \( D_\alpha \) of \( r_{\alpha} \). Then in general, we have

\[
x|_{D_\alpha} = \tau_{\alpha}^2 + a_{\alpha}, \quad y|_{D_\alpha} = b_{\alpha} + b_{1_{\alpha}} \tau_{\alpha} + b_{2_{\alpha}} \tau_{\alpha}^2 + \ldots
\]

and the involution is given by \( \sigma_{\alpha}(\tau_{\alpha}) = -\tau_{\alpha} \). As before, we set the initial condition of the recursion to be \( \omega_{0,1}(p) = ydx \) and \( \omega_{0,2}(p, q) = B(p, q) \), notice that \( \omega_{0,1} \) is now only a locally defined differential form in the vicinity of each \( r_{\alpha} \). The rest of the recursion is the same as above. This variance of topological recursion sometimes called local topological recursion \( \text{[13]} \) and it is the version we are going to be interested in.

### 2.6.2 Relations to Airy structures

Let us introduce the following pre-Airy structure \( \{(H_{TR})_{i=1,2,3,\ldots,\alpha \in \text{Ram}}\} \) on \( W_{\text{Airy}} \) which is a slight modification of \( \{(H_{Airy})_{\alpha \in \text{Airy}}\} \) given in \( \text{(2.62)} \):

\[
(H_{TR})_{2n,\alpha}(w) = \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right) [a] \otimes z^{2n-2} d(z^2) \right),
\]
\[
(H_{TR})_{2n-1,\alpha}(w) = \frac{1}{2} \text{Res}_{z=0} \left( \left( z - \frac{w(z)}{2zdz} \right) \left( z + \frac{w(-z)}{2zdz} \right) [a] \otimes z^{2n-2} d(z^2) \right) \quad (2.70)
\]

for \( n \geq 1 \) where \( w := \sum_{\alpha \in \text{Ram}} \sum_{k=0}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k_{a} \in \text{Ram}} f_{k_{a} \alpha} + y_{k_{a} \alpha} e^{k_{a} \alpha} \in W_{\text{Airy}} \). We note the only change from \( \{(H_{\alpha \in \text{Airy}})\} \) is that \( w(z) \) in one of the factor of \( (H_{TR})_{2n-1,\alpha} \) has been replaced by \( -w(-z) \). Expanding \( (2.70) \) we get

\[
(H_{TR})_{i,\alpha} = -y_{i,\alpha} + (\sigma_{TR})_{(i,\alpha)(j,\beta)(k,\gamma)}^{x_{i,\beta}x_{k,\gamma} + 2(b_{TR})_{(i,\alpha)(j,\beta)}^{y_{i,\beta}y_{k,\gamma} + (c_{TR})_{(i,\alpha)(j,\beta)(k,\gamma)}^{y_{i,\beta}y_{k,\gamma}} \quad (2.71)
\]

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where

\[(a_{TR})_{(i,\alpha)(j,\beta)(k,\gamma)} = \text{Res}_{z=0} \left( \frac{1}{4z} \frac{1}{z(dz)^2} f_{i,\alpha}(z) f_{j,\beta}(z) f_{k,\gamma}(z) \right) \delta_{i,\text{odd}}, \quad A_{TR} := ((a_{TR})_{(i,\alpha)(j,\beta)(k,\gamma)}) \]

\[(b_{TR})_{(i,\alpha)(j,\beta)} = \text{Res}_{z=0} \left( \frac{1}{4z} \frac{1}{z(dz)^2} f_{i,\alpha}(z) f_{j,\beta}(z) e^{\gamma}(z) \right) \delta_{i,\text{odd}}, \quad B_{TR} := ((b_{TR})_{(i,\alpha)(j,\beta)}) \]

\[(c_{TR})_{(j,\beta)(k,\gamma)} = \text{Res}_{z=0} \left( \frac{1}{4z} \frac{1}{z(dz)^2} f_{j,\beta}(z) e^{\gamma}(z) \right) \delta_{i,\text{odd}}, \quad C_{TR} := ((c_{TR})_{(j,\beta)(k,\gamma)}). \]

The expression (2.71) should be compared to (2.34). Additionally, we define \((c_{TR})_{i,\alpha} = \frac{1}{16} \delta_{j,\beta}, c_{TR} = (c_{TR})_{(i,\alpha)} = \epsilon_{Airy}.\) The key point is that \((V_{\text{Airy}}^{\text{Ram}}), A_{TR}, B_{TR}, C_{TR}, e_{TR})\) is a quantum pre-Airy structure. Additionally, since \(-w(-z) = z\) if \(x_{t=\text{even},\alpha\in\text{Ram}} = y_{t=\text{even},0=\text{Ram}} = 0,\) it is clear from (2.70) and Remark 2.5.24 that both \((V_{\text{Airy}}^{\text{Ram}}), A_{TR}, B_{TR}, C_{TR}, e_{TR})\) and \((V_{\text{Airy}}^{\text{Ram}}), A_{Airy}, B_{Airy}, C_{Airy}, e_{Airy})\) contain the same quantum Airy sub-structure \(((V_{\text{Airy}}^{\text{Ram}}), A_{Airy}, B_{Airy}, C_{Airy}, e_{Airy})).\)

We will now present the main result of this section.

**Proposition 2.6.2 (Theorem G, Lemma 9.1, Section 3.1)** Consider a smooth compact Riemann surface \(\Sigma_0\) with a set of distinct points \(\{\alpha\in\text{Ram}\}\) and a neighbourhood \(D_\alpha \supset r_\alpha\) for each \(\alpha\in\text{Ram}\) with local coordinate \(z_\alpha.\) Let \(\{S_{g,n}\in \Gamma((\Sigma_0 \setminus \cup_{\alpha\in\text{Ram}} r_\alpha)^n, (\Omega_{\Sigma_0}^2)^n)\}\) be the multi-differentials produced from topological recursion on \(\Sigma_0\) using:

1. The involution \(\sigma_\alpha(z_\alpha) := -z_\alpha.\)
2. \(\omega_{0,1}(p)\) locally defined on each \(D_\alpha\) for \(\alpha\in\text{Ram}\) such that \(\omega_{0,1}(z_\alpha) - \omega_{0,1}(\sigma_\alpha(z_\alpha)) = 4\pi^2 d z_\alpha.\)
3. \(\omega_{0,2}(p,q) = B(p,q)\) the normalized Bergman kernel.

**Suppose that** \(V_{\Sigma_0}^{\text{mer}} \subset W_{\text{Airy}}^{\text{Ram}}\) is a Lagrangian complement of \(T_0 L_{\text{Airy}}^{\text{Ram}}\) with basis \(\{\eta^{i=1,2,3,\ldots} := \sum_{\beta\in\text{Ram}} \sum_{j=1}^{\infty} \eta^j_{\beta}; (d^j_{\beta})\} : V_{\text{Airy}}^{\text{Ram}} \rightarrow V_{\text{Airy}}^{\text{Ram}}\) and \(\{\epsilon^k_{\beta} := \sum_{\beta,\gamma} \sum_{j=1}^{\infty} \epsilon^j_{\beta}; (d^j_{\beta})\} : V_{\text{Airy}}^{\text{Ram}} \rightarrow V_{\text{Airy}}^{\text{Ram}}\) are given by Definition 2.5.10. Let \((V_{\Sigma_0}^{\text{mer}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, e_{\text{Airy}})\) be the quantum Airy structure obtained from the gauge transformation of the quantum Airy structure \((V_{\text{Airy}}^{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, e_{\text{Airy}})\) (see Section 2.5.4) corresponding to the change of the canonical basis \(\{\eta^{i,\alpha}; f_{k,\alpha}\} \\rightarrow \{\eta^k; \omega_k\}\) of \(W_{\text{Airy}}^{\text{Ram}}.\) Also, let \(\{S_{g,n}\in \text{Sym}_{n}(V_{\Sigma_0}^{\text{mer}})\}\) be the output of the ATR using \((V_{\Sigma_0}^{\text{mer}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, e_{\text{Airy}}).\) Then for \(g \geq 0, n \geq 3\) or \(g \geq 1, n \geq 1,\) we have:

\[
\omega_{g,n}(p_1,\ldots,p_n) = \sum_{i_1,\ldots,i_n=1}^{\infty} S_{g,n;i_1,\ldots,i_n} \eta^1(p_1) \cdots \eta^n(p_n), \tag{2.72}
\]

where \(\eta^1(p_1) \cdots \eta^n(p_n)\) denotes symmetric tensor product \(\sum_{\sigma\in S_n} \frac{1}{n!} \eta^{\sigma(1)}(p_{\sigma(1)}) \cdots \eta^{\sigma(n)}(p_{\sigma(n)}).\)

**Proof:** We let the basis of \(T_0 L_{\text{Airy}}^{\text{Ram}}\) be given by \(\{c_i := \sum_{\beta\in\text{Ram}} \sum_{j=1}^{\infty} c_{i,\beta} f_{j,\beta}\},\) where \(c_{i,\beta} = (d^j_{\beta})^{-1}.\) From Remark 2.6.1 we may write for \(g \geq 0, n \geq 3\) or \(g \geq 1, n \geq 1:\n
\[
\omega_{g,n}(p_1,\ldots,p_n) = \sum_{i_1,\ldots,i_n=1}^{\infty} (s_{TR})_{g,n;i_1,\ldots,i_n} \eta^1(p_1) \cdots \eta^n(p_n).\]

In the following let us assume that \(p\) is close to one of the ramification point but \(p_1\) is further away in the sense that if \(p_1\in U_\alpha \cap \Sigma_0\) were in the neighbourhood of \(r_\alpha,\alpha\in\text{Ram}\) then in standard local coordinates we have \(|z_\alpha(p)| << |z_\alpha(p_1)|.\) The Laurent expansion of \(\omega_{0,2}(p_1,p)\) when \(p\) is close to a ramification point in the standard local coordinates can be written as

\[
\omega_{0,2}(p_1,p) = \sum_{\alpha\in\text{Ram},k>0} \frac{\epsilon^k_{\alpha}(p_1) f_{k,\alpha}(z_\alpha)}{z_\alpha} = \sum_{k>0} \eta^k(p_1) \omega_k(z_\alpha),
\]

where \(z\) is the standard local coordinate corresponding to \(p.\) Similarly, for \(K(p_1,p)\) we have

\[
K(p_1,p) = -\frac{1}{4z_\alpha(dz_\alpha)^2} \sum_{\alpha\in\text{Ram},k>0} \frac{1}{k} \epsilon^k_{\alpha}(p_1) f_{k,\alpha}(z_\alpha).
\]
Now we have everything we need to evaluate the recursion formula. For \( g = 0, n = 3 \) we have

\[
\omega_{0,3}(p_1, p_2, p_3) = 2 \sum_{\alpha \in \text{Ram}} \text{Res}_{p = r_\alpha}(K(p_1, p)\omega_{0,2}(p_2)\omega_{0,2}(\sigma_\alpha(p), p_3))
\]
or,

\[
\sum_{i_1, i_2, i_3 > 0} (STR)_{0,3;i_1i_2i_3} \eta_{0}^{i_1}(p_1)\eta_{0}^{i_2}(p_2)\eta_{0}^{i_3}(p_3)
\]

\[
= 2 \sum_{\alpha_1 \in \text{Ram}, i_1, i_2, i_3 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4i_1} \frac{1}{z_\alpha(dz_\alpha)^2} f_{i_1, \alpha_1}(z_\alpha)\omega_{i_2}(z_\alpha)\omega_{i_3}(-z_\alpha) \right) \bar{e}^{1,\alpha_1}(p_1)\eta^{i_2}(p_2)\eta^{i_3}(p_3).
\]

Comparing the coefficients, we have

\[
(STR)_{0,3;i_1i_2i_3} = 2 \sum_{\alpha_1, \alpha_2, \alpha_3 \in \text{Ram}, j_1, j_2, j_3 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4j_1} f_{j_1, \alpha_1}(z_\alpha) f_{j_2, \alpha_2}(z_\alpha) f_{j_3, \alpha_3}(-z_\alpha) \right) c_{i_1}^{j_1, \alpha_1} c_{i_2}^{j_2, \alpha_2} c_{i_3}^{j_3, \alpha_3}.
\]

For \( g = 1, n = 1 \) we have

\[
\omega_{1,1}(p_1) = \sum_{\alpha \in \text{Ram}} \text{Res}_{p = r_\alpha}(K(p_1, p)\omega_{0,2}(p, \sigma_\alpha(p)))
\]

\[
\sum_{i_1 > 0} (STR)_{1,1;i_1} \eta_{0}^{i_1}(p_1) = \lim_{z_\alpha \to z_\alpha} \sum_{\alpha \in \text{Ram}} \text{Res}_{z_\alpha = r_\alpha}(K(p_1, p)\omega_{0,2}(z_\alpha, -z_\alpha'))
\]

\[
= \lim_{z_\alpha \to z_\alpha} \sum_{\alpha_1, \alpha_2 \in \text{Ram}, i_1, i_2 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4i_1} \frac{1}{z_\alpha(dz_\alpha)^2} f_{i_1, \alpha_1}(z_\alpha) f_{i_2, \alpha_2}(z_\alpha) e^{i_2, \alpha_2}(-z_\alpha') \right) \bar{e}^{1,\alpha_1}(p_1)
\]

\[
+ \lim_{z_\alpha \to z_\alpha} \sum_{\alpha_1, \alpha_2 \in \text{Ram}, i_1, i_2 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4i_1} \frac{1}{z_\alpha(dz_\alpha)^2} f_{i_1, \alpha_1}(z_\alpha) f_{i_2, \alpha_2}(z_\alpha) f_{j_2, \alpha_3}(z_\alpha) \bar{e}^{j_2, \alpha_3}(p_1) \right)
\]

\[
+ \sum_{\alpha_1 \in \text{Ram}, i_1 > 0} \text{Res}_{z_\alpha = 0} \left( \frac{1}{4z_\alpha} \left( z_\alpha' \frac{dz_\alpha}{z_\alpha} \right) \right) \bar{e}^{1,\alpha_1}(p_1)
\]

\[
(STR)_{1,1;i_1} = \sum_{\alpha_1 \in \text{Ram}, j_1 > 0} (\epsilon_{TR})_{j_1, \alpha_1} + \sum_{\alpha_2, \alpha_3 \in \text{Ram}, j_2, j_3 > 0} (a_{TR})_{j_1, \alpha_1; j_2, \alpha_2; j_3, \alpha_3} \bar{s}_{j_2, \alpha_2}(j_2, \alpha_2) \bar{s}_{j_3, \alpha_3}(j_3, \alpha_3) \bar{e}^{j_1, \alpha_1}.\]

Comparing the coefficients, we have

\[
(STR)_{1,1;i_1} = \sum_{\alpha_1 \in \text{Ram}, j_1 > 0} (\epsilon_{TR})_{j_1, \alpha_1} + \sum_{\alpha_2, \alpha_3 \in \text{Ram}, j_2, j_3 > 0} (a_{TR})_{j_1, \alpha_1; j_2, \alpha_2; j_3, \alpha_3} \bar{s}_{j_2, \alpha_2}(j_2, \alpha_2) \bar{s}_{j_3, \alpha_3}(j_3, \alpha_3) \bar{e}^{j_1, \alpha_1}.
\]

For \( g \geq 0, n \geq 4 \) or \( g \geq 1, n \geq 2 \) or \( g \geq 2, n \geq 1 \) we have from the recursion formula

\[
\sum_{i_1, \cdots, i_n > 0} (STR)_{g,n; i_1, \cdots, i_n} \eta^{i_1}(p_1) \cdots \eta^{i_n}(p_n)
\]

\[
= \sum_{\alpha \in \text{Ram}, i_1 > 0} \left[ \sum_{j_1, j_2 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4i_1} \frac{1}{z_\alpha(dz_\alpha)^2} f_{i_1, \alpha_1}(z_\alpha) \eta^{j_1}(z_\alpha) \eta^{j_2}(-z_\alpha) \right) (STR)_{g-1,n+1;j_1,j_2,\cdots,i_n} \right]
\]

\[
+ 2 \sum_{k=2}^{n} \sum_{j_1 > 0} \text{Res}_{z_\alpha = 0} \left( -\frac{1}{4i_1} \frac{1}{z_\alpha(dz_\alpha)^2} f_{i_1, \alpha_1}(z_\alpha) \omega_{i_k}(z_\alpha) \eta^{j_1}(-z_\alpha) \right) (STR)_{g,n-1;j_1,i_2,\cdots,i_{k-1},i_k}.
\]
Comparing the coefficients, we find that the recursion relations (2.69) becomes

\[
(S_{TR})_{g,n,i_1,i_2,i_3} = 2 \sum_{k=2}^{n} \left( b_{TR}^j_{i_1} (S_{TR})_{g,n-1,j_1,i_2,i_3} \right) + \sum_{j_1,j_2>0} \left( \hat{c}_{TR}^{j_1,j_2} (S_{TR})_{g,1,j_1,j_2,i_1,i_2,i_3} \right),
\]

for \( g \geq 0, n \geq 4 \) or \( g \geq 2, n \geq 1 \) or \( g \geq 1, n \geq 2 \) with the initial condition

\[
(S_{TR})_{0,3,i_1,i_2,i_3} = 2(\hat{a}_{TR})_{i_1,i_2,i_3}, \quad (S_{TR})_{1,1,i} = (\hat{c}_{TR}), \quad (S_{TR})_{0,n \leq 2} = (S_{TR})_{g=0,0} = 0
\]

where

\[
\begin{align*}
\hat{a}_{TR}^{j_1,j_2} &= (a_{TR}^{j_1,j_2})_{i_1,i_2,i_3} \hat{c}_{TR}^{j_1,j_2} = (b_{TR}^{j_1,j_2})_{i_1,i_2,i_3}, \\
\hat{c}_{TR}^{j_1,j_2} &= (c_{TR}^{j_1,j_2})_{i_1,i_2,i_3}, \quad (b_{TR}^{j_1,j_2})_{i_1,i_2,i_3} = (\hat{b}_{TR}^{j_1,j_2})_{i_1,i_2,i_3}, \\
\hat{c}_{TR}^{j_1,j_2} &= (\hat{c}_{TR}^{j_1,j_2})_{i_1,i_2,i_3}, \quad (c_{TR}^{j_1,j_2})_{i_1,i_2,i_3} = (\hat{c}_{TR}^{j_1,j_2})_{i_1,i_2,i_3}.
\end{align*}
\]

In (2.75) the summation is over positive odd integers \( j_1 \) and over all positive integers for all other indices. Equivalently, we may take all summations in (2.75) to be over all positive integers since components of \( A_{TR}, B_{TR}, C_{TR}, c_{TR} \) with \( j_1 = \text{even} \) are zero. Let \( A_{TR} = (\hat{a}_{TR})_{i_1,i_2,i_3}, B_{TR} = (\hat{b}_{TR}^{j_1,j_2})_{i_1,i_2,i_3}, C_{TR} = (\hat{c}_{TR}^{j_1,j_2})_{i_1,i_2,i_3} \) and \( \hat{c}_{TR} = (\hat{c}_{TR})_{i_1,i_2,i_3} \). We recognize (2.18) together with (2.74) as the ATR of quantum pre-Airy structure \( (V_{\Sigma_0}^{\text{mer}}, A_{TR}, B_{TR}, C_{TR}, c_{TR}) \) which is the gauge transform of the quantum pre-Airy structure \( (V_{\Sigma_0}^{\text{Ram}}, A_{TR}^{\text{Ram}}, B_{TR}^{\text{Ram}}, C_{TR}^{\text{Ram}}, c_{TR}^{\text{Ram}}) \) corresponding to the change of the canonical basis \( \{ e_{\alpha,k}, f_{k,\alpha} \} \rightarrow \{ \gamma, \omega \} \) of \( W^{\text{Ram}}_{\Sigma_0} \). Using Remark 2.2.30 and Remark 2.5.24 we have that \( (V_{\Sigma_0}^{\text{mer}}, A_{TR}^{\text{Ram}}, B_{TR}^{\text{Ram}}, C_{TR}^{\text{Ram}}, c_{TR}^{\text{Ram}}) \) both contain the quantum Airy substructure \( (V_{\Sigma_0}^{\text{mer}})^{\text{odd}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, c_{\text{Airy}} \). It follows that \( (S_{TR})_{g,n} = S_{g,n} \in Sym_n ((V_{\Sigma_0}^{\text{mer}})^{\text{odd}}) \) (see Remark 2.2.14), which completes the proof.

### 2.7 Topological Recursion and Prepotentials

In this section, we are going to prove the main theorem which relates the prepotential \( \Phi_{\Sigma_0} \) (see Definition 2.1.22), defined on some open neighbourhood \( \mathcal{B}_{\Sigma_0} \supset \Sigma_0 \) of the moduli space \( B \) of \( F \)-transversal genus \( g \) curves in \( (S, \Omega, F) \), to the genus zero part of topological recursion on \( \Sigma_0 \). The basic idea is as follows. The map \( \Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow H_{\Sigma_0} \) embeds \( B_{\Sigma_0} \) into the fiber \( H_{\Sigma_0} \), as the Lagrangian submanifold \( L_{\Sigma_0} \) with \( \overline{\Sigma_0} \) as the generating function. The image of \( \Phi_{\Sigma_0} \) is contained inside the Lagrangian submanifold \( L_{\Sigma_0} \) with \( \overline{\Sigma_0} \). Finally, we use Proposition 2.6.2 to relate \( \Phi_{\Sigma_0} \) to \( \omega_{0,n} \).

The important step in simplifying this result is to use the right gauge when working with the Airy structure \( \{ (H_{\text{Airy}})_{i=1,2,\ldots,\alpha \in \text{Ram}} \} \). For example, the canonical basis

\[
\{ e_{k=1,2,3,\ldots,\alpha \in \text{Ram}} := \{ e_{k=1,2,3,\ldots,\alpha \in \text{Ram}} := \{ e_{k=1,2,3,\ldots,\alpha \in \text{Ram}} := \{ e_{k=1,2,3,\ldots,\alpha \in \text{Ram}} := \{ e_{k=1,2,3,\ldots,\alpha \in \text{Ram}} := \}
\]
for $W_{Ram}^{Airy}$ will not make the comparison between $S_0 = S_0(\{z^k_{a \in Ram}\})$ and $\mathcal{S}_\alpha = \mathcal{S}_\alpha(a^{1, \cdots, \alpha^2})$ easy. Each $x^{k, \alpha}$ is a coefficient of the Laurent series expansion of $\Phi_{\Sigma_\alpha}(\Sigma)$ whereas each $a^\alpha$ relates to $A$-periods of $\Phi_{\Sigma_\alpha}(\Sigma)$. Therefore, we start by choosing the new canonical basis for $W_{Ram}^{Airy}$ which makes the cohomological information of $\Phi_{\Sigma_\alpha}(\Sigma)$ becomes more visible from the point of view of $W_{Ram}^{Airy}$.

**Lemma 2.7.1** Let $[\Sigma_\alpha] \in B$ and let $\{z^{k=1,2,\cdots, \alpha \in Ram}\}$ be the basis of the Lagrangian complement $V_{\Sigma_\alpha}$ as given in Definition 2.5.10. There exists a canonical basis

$$\left\{ \eta^{i=1,2,3,\cdots} : = \sum_{\beta \in Ram} \sum_{j=1}^{\infty} d_{i,j,\beta} \eta^{j,\beta}; \omega_i = 1,2,3,\cdots \right\} = \sum_{\beta \in Ram} \sum_{j=1}^{\infty} c_{i,j,\beta} f_{i,j,\beta} \right\}$$

of $W_{\Sigma_\alpha}^{Ram} \cong W_{Ram}^{Airy}$,

$$\Omega_{Airy}(\omega_i, \omega_j) = \Omega_{Airy}(\eta^i, \eta^j) = 0, \quad \Omega_{Airy}(\eta^i, \omega_j) = \delta^i_j,$n corresponding to the Lagrangian complement $V_{\Sigma_\alpha}$ such that $\omega_1, \cdots, \omega_g \in \Gamma(\Sigma_\alpha, \Omega_{\Sigma_\alpha}^{\beta}), \eta^{i=1,2,3,\cdots} \in V_{\Sigma_\alpha}$ and $\omega_{i > g}$ are locally defined holomorphic forms on $\downarrow_{\alpha \in Ram} \mathcal{D}_{\alpha, M_\alpha}(\Sigma_0) \subset \Sigma_0$ for some $M_\alpha > M_\alpha$. Furthermore, we have that for $i, j = 1, \cdots, g$:

$$\int_{A_i} \omega_j = \delta^i_j, \quad \int_{B_i} \omega_j = \tau_{ij}(\Sigma_0), \quad \int_{A_i} \eta^i = 0, \quad \int_{B_i} \eta^i = 2\pi i \delta^i_j,$n (7.66)

and all $A, B$-periods of $\eta^{i > g}$ vanish. Lastly, $(\epsilon_{i,\alpha}^{j, \beta}) : V_{Airy}^{\frac{1}{2}} \longrightarrow V_{Airy}^{\frac{1}{2}}, (d_{i,j,\beta}) : V_{Airy}^{\frac{1}{2}} \longrightarrow V_{Airy}^{\frac{1}{2}}$ both satisfy Condition 2.4.17 and $(\epsilon_{i,j}^{1,2,3,\cdots})$ is given by Definition 2.5.10.

**Remark 2.7.2** Equivalently, we describe the canonical basis in [2.7.1] as follows. Choose $\{\omega_1, \cdots, \omega_g\}$ to be the set of normalized holomorphic differentials which is a basis for $\Gamma(\Sigma_\alpha, \Omega_{\Sigma_\alpha}^{\beta})$. The set $\{\omega_1, \cdots, \omega_g, \omega_{i > g}\}$ is a basis for $T_{0,L}_{\Sigma_\alpha}^{Ram}$, where $\omega_{i > g}$ are locally defined. The set $\{\eta^1, \cdots, \eta^g, \eta^{i > g}\}$ is a basis for $V_{\Sigma_\alpha}$ because $\int_{A_i} \eta^i = 0$ for all $i = 1, 2, 3, \cdots$ and $\{\eta^{i > g}\}$ is a basis for $G_{\Sigma_\alpha}^\perp$ because all $A, B$-periods of $\eta^{i > g}$ vanish.

It follows that $\{\omega_1, \cdots, \omega_g, \eta^1, \cdots, \eta^g, \eta^{i > g}\}$ is a basis of $G_{\Sigma_\alpha}$ and $\{\omega_1, \cdots, \omega_g, \eta^1, \cdots, \eta^g\}$ is a basis for $H_{\Sigma_\alpha} = H^1(\Sigma_\alpha, \mathcal{C}) = G_{\Sigma_\alpha}/G_{\Sigma_\alpha}$. Finally, $\int_{B_i} \eta^i = 2\pi i \delta^i_j$ for $j = 1, \cdots, g$ can be deduced from $\Omega_{Airy}(\eta^i, \omega_j) = \delta^i_j$.

**Proof:** Let $\{\omega_1, \cdots, \omega_g\}$ be the normalized holomorphic differentials on $\Sigma_0$. $\int_{A_i} \omega_j = \delta^i_j, \int_{B_i} \omega_j = \tau_{ij}(\Sigma_0).$ It is clear that $\{\omega_1, \cdots, \omega_g\}$ is linearly independent in $T_{0,L}_{\Sigma_\alpha}^{Ram} \subset W_{Ram}^{Airy}$. Define

$$(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n} := \left\{ \xi = \sum_{\alpha \in Ram} [\alpha] \otimes \xi_{\alpha} \mid \xi_{\alpha}(z) \in \mathbb{C}[z_{\alpha}] \frac{dz_{\alpha}}{z_{\alpha}}, \xi_{\alpha}(z) \text{ converges for } |z_{\alpha}| < \tilde{M}_\alpha \right\} \subset T_{0,L}_{\Sigma_\alpha}^{Ram}.$$n We take $\{\xi^{i > n, \alpha \in Ram}\}$ to be the basis of $(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$. It follows that $T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$ is an $n|Ram|$-dimensional vector space. By choosing a large enough $n$, the image of $\{\omega_1, \cdots, \omega_g\}$ in $T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$ is linearly independent and we can complement it with $\{\omega_{i+1}, \cdots, \omega_{|Ram|}\}$ such that the image of $\{\omega_1, \cdots, \omega_{n|Ram|}\}$ in $T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$ is a basis for $T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$. Let $\{\omega_{i > n|Ram|}\}$ be given by $\{\omega_{i > n|Ram|}\}$ in $T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n}$ rearranged in some order, for example, let $r : \{0, \cdots, |Ram| - 1\} \rightarrow Ram$ be an arbitrary bijection then we define $\omega_i := f_{i/r(|Ram|)} \cdot r(i \mod |Ram|)$. Then $\{\omega_1, \cdots, \omega_g\}$ is a basis of $(T_{0,L}_{\Sigma_\alpha}^{Ram}/(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n})$ and $(T_{0,L}_{\Sigma_\alpha}^{Ram})_{> n} \cong T_{0,L}_{\Sigma_\alpha}^{Ram}$. In particular, $(d_{i,j}^{\beta})$ satisfies Condition 2.4.17. It follows that its inverse $(d_{i,j}^{\beta})$ also satisfies Condition 2.4.17 and that $\eta^{i=1,2,3,\cdots, \omega_{i=1,2,3,\cdots}}$ gives a canonical basis for $W_{Ram}^{Airy}$. Since $\eta^i = \sum_{\beta \in Ram} \sum_{j=1}^{\infty} d_{i,j,\beta} \eta^j, \beta$ is a finite summation for each $i$, we have $\eta^i \in \mathcal{S}_\alpha$, in particular that $\int_{A_i} \eta^i = 0$. Suppose that $i > g$ and $j = 1, \cdots, g$ then by using (2.55) we have $\int_{B_i} \eta^i = 2\pi i \Omega_{Airy}(\eta^i, \omega_j) = 0$. Similarly, by using (2.55) for $i, j = 1, \cdots, g$ we have $\int_{B_i} \eta^i = 2\pi i \Omega_{Airy}(\eta^i, \omega_j) = 2\pi i \delta^i_j$. □

The main theorem is a joint work by Paul Norbury, Michael Swaddle and Mehdi Tavakol which we will now state and prove:
Chapter 2. Airy Structures and Deformation of Curves

Theorem 2.7.3 Let $\mathcal{B}$ be the moduli space of $\mathcal{F}$-transversal genus $g$ curves in a foliated symplectic surface $(S, \Omega_S, \mathcal{F})$. Then for some small open neighbourhood $\mathcal{B}_{\Sigma_0} \subset \mathcal{B}$ of the reference point $[\Sigma_0] \in \mathcal{B}$, the prepotential $\tilde{\Phi}_{\Sigma_0} = \tilde{\Phi}_{\Sigma_0}(a^1, \cdots, a^g)$ such that

$$a^i := a^i(\Sigma) = \oint_{A_i} \theta_{\Sigma}, \quad b_i := b_i(\Sigma) = \oint_{B_i} \theta_{\Sigma} = \frac{\partial \tilde{\Phi}_{\Sigma_0}(\{a^k\})}{\partial a^i}, \quad i = 1, \cdots, g.$$ 

can be expressed as

$$\tilde{\Phi}_{\Sigma_0}(a^1, \cdots, a^g) = \tilde{\Phi}_{\Sigma_0}(a^1_0, \cdots, a^g_0)$$

$$+ \sum_{i=1}^g (a^i - a^i_0) \frac{\partial \tilde{\Phi}_{\Sigma_0}}{\partial a^i}(a^1_0, \cdots, a^g_0) + \frac{1}{2} \sum_{i,j=1}^g (a^i - a^i_0)(a^j - a^j_0) \frac{\partial^2 \tilde{\Phi}_{\Sigma_0}}{\partial a^i \partial a^j}(a^1_0, \cdots, a^g_0)$$

$$+ \sum_{n=3}^{\infty} \frac{1}{n!} \left( \frac{1}{2 \pi i} \right)^{n-1} \sum_{i_1, \cdots, i_n=1}^g \left( \oint_{p_1 \in B_{i_1}} \cdots \oint_{p_n \in B_{i_n}} \omega_{0, n}(p_1, \cdots, p_n) \right) (a^{i_1} - a^{i_1}_0) \cdots (a^{i_n} - a^{i_n}_0)$$ (2.77)

for all $(a^1, \cdots, a^g) = ([\Sigma] \in \mathcal{B}_{\Sigma_0}$). Where $a^1_0 := a^k(\Sigma_0)$ and the multi-differentials $\omega_{0,n}(\{\Sigma_0, \cup \alpha \in \text{Ram}^{\alpha}(\Sigma), (\Omega_{\Sigma_0}^2)^n\})$ are produced from topological recursion on $\Sigma_0$ using:

1. The involution $\sigma_{\alpha}(z_\alpha) := -z_\alpha$.
2. $\omega_{0,1}(p)$ locally defined on each $\Sigma_0 \cap U_\alpha$ for $\alpha \in \text{Ram}$ such that $\omega_{0,1}(z_\alpha) - \omega_{0,1}(\sigma_{\alpha}(z_\alpha)) = 4z_\alpha d\alpha$.
3. $\omega_{0,2}(p,q) = B(p,q)$ the normalized Bergman kernel.

with $z_\alpha$ for $\alpha \in \text{Ram}$ denotes the standard local coordinates corresponding to the collection of $(\mathcal{F}, \Omega_{\Sigma_0})$-charts $U_{\text{Ram}} = \{(U_\alpha \in \text{Ram}, x_\alpha \in \text{Ram}, y_\alpha \in \text{Ram})\}$, $r_\alpha(\Sigma_0) \in \Sigma_0 \cap U_\alpha$ such that $\gamma_{\alpha}(\Sigma_0) = (x_\alpha = z_\alpha^2, y_\alpha = z_\alpha)$.

Proof: Let $\{\epsilon_\alpha \in \text{Ram}\}, \{L_\alpha \in \text{Ram}\}, U_{\text{Ram}}$ and $B_{\Sigma_0}$ be chosen such that Condition 2.5.2 is satisfied. In particular, the collection of $(\mathcal{F}, \Omega_{\Sigma_0})$-charts $U_{\text{Ram}}$ is chosen such that $\gamma_{\alpha}(\Sigma_0) = (x_\alpha = z_\alpha^2, y_\alpha = z_\alpha)$. Consider the embedding map $\Phi_{\Sigma_0} : B_{\Sigma_0} \rightarrow G_{\Sigma_0}$ given by $\Phi_{\Sigma_0}(\Sigma) := -\beta_\Sigma + \sigma_{\Sigma} \theta_{\Sigma}$ (see Section 2.5.7). It follows from Proposition 2.5.38 that $i(\Phi_{\Sigma_0}(\Sigma))$ satisfies the Ram product analytic residue constraints:

$$i(\Phi_{\Sigma_0}(\Sigma)) = \Phi_{\Sigma_0}(\Sigma) = \sum_{\alpha \in \text{Ram}} \sum_{k=1}^g (x^k \alpha f_{k,\alpha} + y_k \alpha e^{k,\alpha}) \in \mathcal{L}_{\text{Airy}} \subset W_{\text{Airy}}.$$ (2.78)

Let us change the canonical basis of $W_{\text{Airy}}$ to $\{\eta^1, \cdots, \eta^g, \omega_1, \cdots, \omega_g\}$ as provided by Lemma 2.7.1. Then

$$\Phi_{\Sigma_0}(\Sigma) = \sum_{k=1}^g \beta_k \eta^k + \sum_{k=1}^g \alpha^k \omega_k.$$ (2.79)

by Proposition 2.4.26 where $\{\alpha^k \in 1, 2, \cdots, \}, \{\beta_k \in 1, 2, \cdots, \}$ are given by (2.64) and $\alpha^{i} \geq g = 0$ since $\omega^{i} \geq g \notin G_{\Sigma_0}$ (alternatively, we could apply Corollary 2.5.16). Computing the $A$-periods of $\Phi_{\Sigma_0}(\Sigma)$ using (2.76), we obtain for $i = 1, \cdots, g$:

$$\alpha^i = \oint_{A_i} \left( \sum_{k=1}^g \beta_k \eta^k + \sum_{k=1}^g \alpha^k \omega_k \right)$$

$$= \oint_{A_i} \Phi_{\Sigma_0}(\Sigma) = \oint_{A_i} \Phi_{\Sigma_0}(\Sigma) = -\oint_{A_i} \theta_{\Sigma} + \oint_{A_i} \theta_{\Sigma} = a^i(\Sigma) - a^i(\Sigma_0).$$ (2.80)

Similarly, computing $B$-periods of $\Phi_{\Sigma_0}(\Sigma)$ using (2.76), we obtain for $i = 1, \cdots, g$:

$$2\pi i \beta_i + \sum_{k=1}^{\infty} \tau_k(\Sigma_0) \alpha^k = \oint_{B_i} \left( \sum_{k=1}^g \beta_k \eta^k + \sum_{k=1}^g \alpha^k \omega_k \right)$$

$$= \oint_{B_i} \Phi_{\Sigma_0}(\Sigma) = \oint_{B_i} \Phi_{\Sigma_0}(\Sigma) = -\oint_{B_i} \theta_{\Sigma} + \oint_{B_i} \theta_{\Sigma} = b_i(\Sigma) - b_i(\Sigma_0).$$ (2.81)

Where we have used Lemma 2.5.13 in conjunction with the fact that $(\delta_{\alpha}^i)$ satisfies (2.4.17) to justify the term-by-term integration. In particular for each $i = 1, 2, 3, \cdots, \eta^i$ is a finite linear combination of $\epsilon^i, \alpha$. We also
have used the relation \( \Phi_{M}(\Sigma) = \Phi_{\Sigma}(\Sigma) \) from Proposition 2.5.38. From now on we will write \( a' := a'(\Sigma), b_i := b_i(\Sigma) \) and \( a_0' := a'(\Sigma), b_0' := b(\Sigma) \).

Let us cover \( B_{\Sigma_0} \) with a coordinates chart \( (B_{\Sigma_0}, u^1, \ldots, u^g) \). Then it is clear from construction that for each \( a \in \text{Ram}, \, t_a(\Phi_{\Sigma}(\Sigma)) \) is holomorphic in \( \{u^1, \ldots, u^g, z_0\} \) for all \((u^1, \ldots, u^g, z_0) \in B_{\Sigma_0} \times \mathcal{K}_{\alpha,\varepsilon,M_{\alpha}} \). Recall from Lemma 2.1.21 that \( \{a^1, \ldots, a^g\} \) is also a coordinates system of \( B_{\Sigma_0} \). From (2.79) and (2.80), it follows that \( \beta_i \) are holomorphic functions in \( \{a^1, \ldots, a^g\} \). It follows that \( \alpha \to \beta_k(\alpha, \ldots, a^g) \) is holomorphic in \( \{a^1, \ldots, a^g, z_0\} \) on the open neighbourhood \( B_{\Sigma_0} \) of \( (a^1, \ldots, a^g) = (0, \ldots, 0) \) and \( |z_0| > \varepsilon_0 \). Using (2.78) together with Proposition 2.4.29 implies that

\[
(\mathcal{H}_{\text{Airy}})(\beta_k(\alpha, \ldots, a^g)) = 0,
\]

where \( (\mathcal{H}_{\text{Airy}}) \) is the gauge transformed Ram product residue constraints Airy structure as given in (2.65). Using the obvious generalization of Proposition 2.4.21 (see also Remark 2.5.25), we conclude that \( \beta_i(\alpha, \ldots, a^g) = (\delta_i S_0)_{\alpha^k \delta^g = 0} \) where \( S_0 = \sum_{n=1}^{\infty} S_{0,n} \in \mathbb{P}_{\infty} \) is the output of the ATR using the quantum Airy structure \((V_{\text{Airy}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \varepsilon_{\text{Airy}})\). Here, \((V_{\text{Airy}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \varepsilon_{\text{Airy}})\) is the quantum Airy structure obtained from the gauge transformation of the quantum Airy structure \((V_{\text{Ram}}, A_{\text{Ram}}, B_{\text{Ram}}, C_{\text{Ram}}, \varepsilon_{\text{Ram}})\), corresponding to the change of a canonical basis of \( W_{\text{Ram}} \) from \( \{e^{k=1,2,3}, \ldots, a^g \in \text{Ram}, f^{k=1,2,3}, \ldots, a^g \in \text{Ram}\} \) to \( \{\eta^{k=1,2,3}, \omega^{k=1,2,3}, \ldots\} \) (see Section 2.5.4). In particular, let \( S_0(\alpha, \ldots, a^g) := S_0(\{\alpha^1, \ldots, a^g, \alpha^{k \geq g} = 0\}) \) then \( S_0 \) is holomorphic on \( B_{\Sigma_0} \) and \( \beta_i(\alpha, \ldots, a^g) = \frac{\partial S_0}{\partial \alpha^i}(\alpha, \ldots, a^g) \) for \( i = 1, \ldots, g \). Equivalently, \( \beta_i = \frac{\partial S_0}{\partial \alpha^i}(\alpha^1, \ldots, a^g, \alpha^{k \geq g}) \) for \( i = 1, \ldots, g \). From (2.78) and (2.80) implies

\[
2\pi i \frac{\partial S_0}{\partial \alpha^i}(\alpha^1, \ldots, a^g, \alpha^{k \geq g}) + \sum_{k=1}^{g} (a^k - a^k_0) \frac{\partial^2 S_0}{\partial a^k \partial \alpha^i}(\alpha^1, \ldots, a^g) = \frac{\partial S_0}{\partial \alpha^i}(\alpha^1, \ldots, a^g) - \frac{\partial S_0}{\partial a^i}(\alpha^1, \ldots, a^g).
\]

Integrating both sides, we find that for all \( (a^1, \ldots, a^g) = \Sigma \in B_{\Sigma_0} \) we have

\[
\mathfrak{g}_{\Sigma}(a^1, \ldots, a^g) = \mathfrak{g}_{\Sigma}(a^1_0, \ldots, a^g_0) + \sum_{i=1}^{g} (a^i - a^i_0) \frac{\partial^2 S_0}{\partial a^i \partial \alpha^i}(a^1_0, \ldots, a^g_0) + \sum_{i,j=1}^{g} \frac{\partial^2 S_0}{\partial a^i \partial a^j}(a^1_0, \ldots, a^g_0) + 2\pi i S_0(a^1 - a^1_0, \ldots, a^g - a^g_0).
\]

From (2.23), \( S_0 = \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{i_1, \ldots, i_n=1}^{\infty} S_{0,n;i_1,\ldots,i_n} \alpha^{i_1} \cdots \alpha^{i_n} \) it follows that

\[
S_0(a^1 - a^1_0, \ldots, a^g - a^g_0) = \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{i_1, \ldots, i_n=1}^{\infty} S_{0,n;i_1,\ldots,i_n} (\alpha^{i_1} - \alpha^{i_1}_0) \cdots (\alpha^{i_n} - \alpha^{i_n}_0).
\]

On the other hand, Proposition 2.6.2 and the fact that \( f_B \), \( \eta^j = 0 \) if \( j > g \) and \( f_B \), \( \eta^j = 2\pi i \delta^j \) if \( j \leq g \) implies that for \( i_1, \ldots, i_n = 1, \ldots, g \) we have

\[
S_{0,n;i_1,\ldots,i_n} = \frac{1}{2\pi i} \int_{B_{\Sigma_1}} \cdots \int_{B_{\Sigma_n}} \omega_{0,n}(p_1, \ldots, p_n).
\]

Combining (2.82), (2.83) and (2.84) the theorem is proven. \( \square \)

**Remark 2.7.4** In Theorem 2.7.3 we can take \( \omega_{0,1}(z_0) = y_0 dx_0 \) but other choices for \( \omega_{0,1}(p) \) are equally valid as long as \( \omega_{0,1}(z_0) - \omega_{0,1}(z_0) = 4\pi e_0 dx_0 \) is satisfied. Note that although \( \omega_{0,1}(z_0) = y_0 dx_0 \) looks very similar to \( -\theta_{\Sigma_0} \), which locally takes the form \( \theta_{\Sigma_0}(z_0) = -(y_0 + x_0)p_0 \cdot dx_0 \), in general \( \omega_{0,1} \) and \( -\theta_{\Sigma_0} \) cannot be the same. Firstly, \( \omega_{0,1} \) is usually defined only locally near ramification points whereas \( \theta_{\Sigma_0} \) is defined on \( \Sigma_0 \cup U_\alpha \in \text{Ram} \). Moreover, it is generally not true that \( \theta_{\Sigma_0}(z_0) = \theta_{\Sigma_0}(z_0) = 4\pi e_0 dx_0 \) so we cannot choose \( \omega_{0,1} = \theta_{\Sigma_0} \). For example, let \( [\Sigma_1] \in B_{\Sigma_0} \) be a nearby curve of \( \Sigma_0 \) with the local parameterization:

\[
\gamma_0(\Sigma_1) = (z_0 = x_0^2 + a_0(\Sigma_1), y_0 = b_0(\Sigma_1) + b_1(\Sigma_1) z_0 + b_2(\Sigma_1) z_0^2 + \cdots).
\]

Let us construct \( \theta \in \Gamma(B_{\Sigma_0}, G) \) by patching together \( \theta_{\Sigma_1}: \Sigma_1 \times \mathbb{C} \rightarrow \mathbb{C} \) as explained in Section 2.5.7 (replacing \( B_{\Sigma_0} \) by \( B_{\Sigma_0} \cap B_{\Sigma} \), if necessary). As in the proof of Lemma 2.5.34 on the annulus \( \mathcal{A}_{\alpha,\varepsilon,M_{\alpha}}(\Sigma_0) \subset \Sigma_0 \cup U_\alpha \), we have

\[
\theta_{\Sigma_0}(z_0) = \theta_{\Sigma_0}(z_0) - \exp \left( -a_0(\Sigma_1) C_{\Sigma} \right) \theta_{\Sigma_0}(z_0).
\]
\[
\theta_{\Sigma_0}(z_0) - \theta_{\Sigma}(z) = 4z_0^2 d\alpha - 2 \sum_{k=0}^{\infty} b_{2k+1}\alpha(S) \left( \sqrt{\frac{2 - \alpha(S)}{z_0^2}} \right)^{2k+1} d(z_0^2) \neq 4z_0^2 d\alpha.
\]

However, in some exceptional cases such as those we are going to examine in the examples below, we can technically set \( \omega_{1,0} := -\theta_{\Sigma_0} \). Suppose that there exists a meromorphic differential form \( dS(\Sigma) \) on each \( \Sigma \in \mathcal{B}_{\Sigma_0} \), varying holomorphically over \( \mathcal{B}_{\Sigma_0} \), such that \( \nabla_x dS(\Sigma) = \phi_\Sigma \) and \( dS(\Sigma)|_{\Sigma_T u_0} = -(y_0 + f_\alpha(x_0))d\alpha|_{\Sigma_T u_0} \) for some holomorphic function \( f_\alpha(x_0) \) for all \( \alpha \in \mathrm{Ram} \). Then we can define the map \( \Psi_{\Sigma_0} : \mathcal{B}_{\Sigma_0} \to G_{\Sigma_0} \) by \( \Psi_{\Sigma_0}( \Sigma ) = -dS(\Sigma) + s_{\Sigma_0}^* dS(\Sigma) \). If \( dS(\Sigma) \) has no residues, then it effectively plays the role of \( \theta_{\Sigma_0} \), even though \( dS(\Sigma) \) might not be in \( G_{\Sigma_0} \) because it may have poles at non-ramification points on \( \Sigma \). In particular, we can set \( \theta_{\Sigma_0} := [dS(\Sigma_0)] \in \mathcal{H}_{\Sigma_0} \). Since \( (dS(\Sigma_0))(z_0) = 4z_0^2 d\alpha \), we can apply Theorem 2.7.3 with \( \omega_{1,0} := -\theta_{\Sigma_0} \). Example 2.7.5 below provides an example of this scenario.

**Example 2.7.5** Let us consider the family of curves arising from the Hitchin systems [20, 3]. Let \( \mathcal{M}_{n,d} \) be the moduli space of rank \( n \) degree \( d \) semi-stable Higgs Bundles on a compact genus \( g \) Riemann surface \( C \). Given a holomorphic vector bundle \( E \), we define the degree by \( \deg E := \int_C c_1(E) \). A rank \( n \) degree \( d \) semi-stable Higgs Bundle is a pair \((E, \Phi)\), where \( E \) is a rank \( n \) holomorphic vector bundle on \( C \) and \( \Phi : E \to E \oplus \Omega_C^1 \) is a bundle map, such that

\[
\frac{\deg F}{\text{rank } F} \leq \frac{\deg E}{\text{rank } E}
\]

for every sub-bundle \( F \subset E \) such that \( \Phi|_F : F \to F \oplus \Omega_C^1 \). We say that \( (E, \Phi) \) is stable if the inequality is strict.

Let \( \mathcal{B} := \bigoplus_{k=1}^{\infty} \Gamma(C, \Omega_C^{2k}) \) be the base of the Hitchin map \( h : \mathcal{M}_{n,d} \to \mathcal{B} \) given by \( h(E, \Phi) = (p_1(\Phi), \ldots, p_n(\Phi)) \) where \( x^n + p_1(\Phi)x^{n-1} + \cdots + p_n(\Phi) = det(x \cdot I_d - \Phi) \). A fiber of the Hitchin map over \( b = (b_1, \ldots, b_n) \in \mathcal{B} \) can be described by a spectral curve \( S_\theta \subset C \) given by the zero divisor of the following global section:

\[
\lambda^n + \pi^* b_1 \lambda^{n-1} + \cdots + \pi^* b_n = \Gamma(C, \pi^*(\Omega_C^1)^{\otimes n}).
\]

Where \( \pi : T^* C \to C \) is the projection morphism and \( \lambda \in \Gamma(T^* C, \pi^* \Omega_C^1) \) denotes the tautological section: \( \lambda(p) = p \in (\pi^* \Omega_C^1)_p \).

It follows that \( B \) is a family of genus \( g := 2n^2(g - 1) + 2 \) compact Riemann surfaces \( \Sigma \) embedded inside the foliated symplectic surface \((S, \Omega_S, F)\) where \( S := T^* C \) is given by the cotangent fibers and \( \Omega_S := -d\Theta \) where \( \Theta \in \Gamma(T^* C, \pi^* \Omega_C^1) \) is the tautological 1-form. Denote by \( B^{reg} \), the regular locus of \( B \) where \( \Sigma \) are smooth for all \( \Sigma \in B^{reg} \). For each \( \Sigma \in B^{reg} \) we define \( \theta_{\Sigma} := -\Theta|_\Sigma \in \Gamma(\Omega^{1}_{\Sigma}) \). Let \( U \subset C \) be an open subset with local coordinate \( q \), then \((T^* U, q, p), T^* U \subset T^* C \) is a (\( F, \Omega_S^1 \))-chart because \( \Theta|_{T^* U} = dpq \) means \( \Omega_S|_{T^* U} = dq \land dp \) and the foliation is given by \( p = const \). Moreover, we have \( \theta_{\Sigma}|_{T^* U} = dpq|_{T^* U} \) which implies \( \nabla_x \theta_{\Sigma} = \phi_{\Sigma} \).

Let

\[
z^i := \int_{A_i} \theta_{\Sigma}, \quad w_i := \int_{B_i} \theta_{\Sigma} = \frac{\partial \xi_{\Sigma}}{\partial z^i}(z^1, \ldots, z^g)
\]

where \( \xi_{\Sigma} \) is the prepotential. In fact, in this case the prepotential is simple enough to be written down explicitly: \( \xi_{\Sigma}(z^1, \ldots, z^g) = \sum_{i=1}^g w_i z^i = \frac{1}{2} \sum_{j=1}^g \tau_j(z^1, \ldots, z^g) z^j \).

**Example 2.7.6** Let \( \mathcal{B} \) be the family of smooth Seiberg-Witten curves (see Section 1.1):

\[
\Sigma(u) : A^{g+1} \left( w + \frac{1}{w} \right) = z^{g+1} + u z^{g-1} + \cdots + u^l = : P(z; u).
\]
It can be shown that each Seiberg-Witten curve $\Sigma(u)$ can be embedded inside a foliated symplectic surface $(S, \Omega_S, F)$ where $S$ is a certain compactification of $\mathbb{C}^2$. Let us consider the dense subset $U := (\mathbb{C} \setminus (-\infty, 0]) \times \mathbb{C} \subset S$ with coordinates $(\log w, z)$ and suppose without loss of generality that $\Sigma_0 = \Sigma(u_0)$ is chosen such that all ramification points $r_\alpha(\Sigma_0)$ are contained in $U$ (we simply pick a different branch-cut for log otherwise). On $U$, the symplectic form is $\Omega|_U = \frac{dw}{w} \wedge dz$ and the foliation is given by $w = \text{const}$, hence $(U, \log w, z)$ is a $(F, \Omega_S)$-chart. The Seiberg-Witten differential is given by $dS_{SW} := \frac{dw}{w}$, or $dS_{SW}(\Sigma(u)) = z \frac{dw}{w}|_{\Sigma(u)}$ if we would like to emphasize that we are considering $dS_{SW}$ as a differential form on $\Sigma(u)$. We define $A, B$-periods and the Seiberg-Witten prepotential $F_{SW}^{\Sigma_0} = F_{SW}^{\Sigma_0}(a^1, \ldots, a^g)$ by
\[
a^i := \int_{A_i} dS_{SW}(\Sigma(u)), \quad b_i := \int_{B_i} dS_{SW}(\Sigma(u)) = \frac{\partial F_{SW}^{\Sigma_0}}{\partial a^i}(a^1, \ldots, a^g),
\]
over some open neighbourhood $B_{\Sigma_0}$ of $[\Sigma_0] \in B$. By definition of the symplectic form $\Omega_S$, we can see that $\nabla_F dS_{SW}(\Sigma(u)) = -\phi_{\Sigma(u)}$ and hence $\theta_{S_{SW}} := -[dS_{SW}(\Sigma(u))] \in H_{\Sigma(u)}$. The negative sign means that we will need to identify $a^i := -a^i$ and $F_{SW}^{\Sigma_0}(a^1, \ldots, a^g) = F_{SW}^{\Sigma_0}(a^1, \ldots, a^g)$ after our application of Theorem \ref{thm:TopologicalRecursion} later on. Choose a new $(F, \Omega_S)$-chart $(U_0, x_0, y_0)$ around every ramification points $r_\alpha$ of $\Sigma_0$ such that $\gamma_\alpha(\Sigma_0) = (x_0 = z_0^2, y_0 = z_0)$. Then $(\log w, z)$ and $(x_0, y_0)$ must be related by the coordinate transformation of the form \ref{eq:CoordinateChange}:
\[
\log w = F_\alpha(x_0), \quad z = y_0 + G'(x_0).
\]
Therefore,
\[
(dS_{SW}(\Sigma_0))(z_0) - (dS_{SW}(\Sigma_0))(-z_0) = \left( y_0(z_0) + G'(x_0(z_0)) \right) F'(x_0(z_0)) dx_0(z_0)
- \left( y_0(-z_0) + G'(x_0(-z_0)) \right) F'(x_0(-z_0)) dx_0(-z_0)
= y_0(z_0) dx_0(z_0) - y_0(-z_0) dx_0(-z_0) = 4z_0^2 dz_0.
\]
Using Theorem \ref{thm:TopologicalRecursion} we find that on some $B_{\Sigma_0} \subseteq B$ the relation \ref{eq:RelationBetweenPrepotentials} holds between the Seiberg-Witten prepotential $F_{SW}^{\Sigma_0}$ and $\omega_{0,n}$ produced from topological recursion on $\Sigma_0$ using $\omega_{0,1} := dS_{SW}(\Sigma_0)$ and $\omega_{0,2} = B$, where $B = B(p, q)$ is the normalized Bergman kernel on $\Sigma_0$. In Chapter \ref{chapter:Examples} we are going to study this example in more detail. In particular, we will construct the needed foliated symplectic surface $(S, \Omega_S, F)$ and explicitly show the calculations leading to \ref{eq:RelationBetweenPrepotentials} without referring to Theorem \ref{thm:TopologicalRecursion}.
Chapter 3

Seiberg-Witten Prepotential and Topological Recursion

In this chapter we demonstrate the Kontsevich-Seibelman approach to topological recursion we have studied in Chapter 2 using an explicit example of the genus $g \geq 1$ Seiberg-Witten family of curves, parameterized by $u = (u_1, \ldots, u_g)$:

$$\Lambda^{g+1} \left( w + \frac{1}{w} \right) = z^{g+1} + u_g z^{g-1} + \cdots + u_1 =: P(z; u).$$

In the end, we obtain the formula (3.27) relating the Seiberg-Witten prepotential $\mathcal{F}^{SW}_0 = \mathcal{F}^{SW}_0\{\{a^i\}\}$ to the genus zero part of topological recursion on a Seiberg-Witten curve with $\omega_{0,1} = dS_{SW}(\Sigma)$ on some open neighbourhood $B_{\Sigma_0} \subseteq B$ of $[\Sigma_0] \in B$. Note that the energy scale parameter $\Lambda$ plays no role here and we will set $\Lambda = 1$.

Alternatively, we can simply absorb $\Lambda$ into $u_k$ and $z$ by re-defining $\frac{w^k}{\Lambda^{g+1} - \Lambda} \mapsto u_k$ and $\frac{1}{\Lambda} \mapsto z$. First, we will show in Section 3.1 that the family of smooth Seiberg-Witten curves

$$B := \{ u = (u_1, \ldots, u_g) \in \mathbb{C}^g \mid P^2(z; u) - 4 = 0 \text{ has } 2g + 2 \text{ distinct roots} \}$$

is the moduli space of $\mathcal{F}$-transversal genus $g$ curves in some foliated symplectic surface $(S, \Omega_S, \mathcal{F})$. Once this is done, using Theorem 2.7.3 the formula (3.27) immediately follows. However, the purpose of this chapter is to demonstrate various calculations in Chapter 2 in the light of the Seiberg-Witten family of curves. Therefore, in the remainder of this chapter, we will not refer to Theorem 2.7.3, in fact, we will re-prove the Seiberg-Witten case of Theorem 2.7.3 in Section 3.3. Some other relevant details will be presented in Section 3.2 such as the choice of $\{e_{a \in \text{Ram}}\}, \{U_{a \in \text{Ram}}\}, U_{\text{Ram}}, B_{\Sigma_0}$ and the verification of Proposition 2.5.38 in the context of Seiberg-Witten family of curves.

3.1 Embedding of Seiberg-Witten Family of Curves into a Foliated Symplectic Surface

3.1.1 Outline of the construction of the foliated symplectic surface $(S, \Omega_S, \mathcal{F})$

To apply the technique we have discussed in Chapter 2 we need to find a foliated symplectic surface $(S, \Omega_S, \mathcal{F})$, such that any smooth genus $g \geq 1$ Seiberg-Witten curve $\Sigma(u)$, in the family $B$, can be embedded into $S$ as an $\mathcal{F}$-transversal curve. We require that $S$ contains a dense open subset $U = \mathbb{C}^* \times C$ where $\mathbb{C}^* := \mathbb{C} \setminus \{0\}$, which can be covered using two $(\mathcal{F}, \Omega_S)$-charts $(U_i, \log w, z), i = 1, 2$ given by any two different branch-cuts of log, $\Omega_S|_U = \frac{dw}{w} \wedge dz$ and the foliation given by $w = \text{const}$. This is so that the section $\theta \in \Gamma(B_{\Sigma_0}, G)$ introduced in Section 2.5.7 will be related to the Seiberg-Witten differential $dS_{SW} = \frac{dz}{w}$. In other words: if $dS_{SW}$ is treated as a differential form on $U$ then $d(dS_{SW})|_U = \Omega_S|_U$.

Remark 3.1.1 We cannot simply set $S = \mathbb{C}^* \times C$ or $\mathbb{C}^2$ because Seiberg-Witten curves $\Sigma(u)$ are non-compact as curves in $\mathbb{C}^* \times C$ or $\mathbb{C}^2$.

There are many ways to construct $(S, \Omega_S, \mathcal{F})$ but let us now describe one of the possible ways. We embed Seiberg-Witten curves $\Sigma(u)$ into $\mathbb{P}^2$ as follows

$$\Sigma(u) := \{ [w : z : x] \in \mathbb{P}^2 \mid w^2 x^g - w(z^{g+1} + u_g x^{g-1} + \cdots + u_1 x^{g+1}) + x^{g+2} = 0 \} \subset \mathbb{P}^2.$$
When $g > 1$ the curve $\Sigma(u)$ embeds non-smoothly into $\mathbb{P}^2$ with a singular point of multiplicity $g$ at $[w : z : x] = [1 : 0 : 0]$. There also exists no globally defined holomorphic symplectic forms on $\mathbb{P}^2$ because the canonical divisor of $\mathbb{P}^2$ is $K_{\mathbb{P}^2} \sim -3H$, where $H$ is the hyperplane divisor. In other words, any symplectic form on $\mathbb{P}^2$ is meromorphic with pole divisor a degree 3 curve. If $\Sigma(u)$ intersects $K_{\mathbb{P}^2}$ trivially we could still consider $S$ to be an open subset of $\mathbb{P}^2$ containing $\Sigma(u)$ but not $K_{\mathbb{P}^2}$, hence it is symplectic. However, Bézout’s theorem guarantees that $\Sigma(u)$ intersects $K_{\mathbb{P}^2}$ at $3(g+2)$ points counting multiplicity. For these reasons, we cannot simply take $S$ to be $\mathbb{P}^2$ or any open subset of $\mathbb{P}^2$.

In particular, let us consider $\Omega_{\mathbb{P}^2} := \frac{\partial (w/x)}{w/x} \wedge \left( \frac{1}{x} \right)$. We define divisors $H_w := \{w = 0\}, H_x := \{x = 0\}$ and $H_z := \{z = 0\}$ on $\mathbb{P}^2$. Then it is clear that $\Omega_{\mathbb{P}^2}$ reduces to $dz \wedge \frac{dz}{w}$ on $\mathbb{C}^2 \setminus H_x$ where we can set $x = 1$. We can see that $\Omega_{\mathbb{P}^2}$ has order 1 pole along the hyperplane $H_w \subset \mathbb{P}^2$ and order 2 pole along $H_z \subset \mathbb{P}^2$. Hence the canonical divisor is

$$K_{\mathbb{P}^2} = (\Omega_{\mathbb{P}^2}) = -H_w - 2H_x$$

and $\Sigma(u)$ intersects $K_{\mathbb{P}^2}$ at $[w : z : x] = [0 : 1 : 0]$ and $[w : z : x] = [1 : 0 : 0]$.

We are going to show that the symplectic surface $S$ can be obtained by blowing-up $\mathbb{P}^2$ repeatedly starting from points $[0 : 1 : 0]$ and $[1 : 0 : 0]$ until $\Sigma(u)$ no longer intersects the canonical divisor.

![Figure 3.1:](image)

$\mathbb{P}^2$ with divisors $H_w := \{w = 0\}, H_x := \{x = 0\}$ and $H_z := \{z = 0\}$. The numbers are order of poles of $\Omega_{\mathbb{P}^2}$ on each respective divisor. We notice that $\Sigma(u)$ intersects the point $[w : z : x] = [1 : 0 : 0]$ tangentially to $H_x$ and intersects $[w : z : x] = [0 : 1 : 0]$ tangentially to $H_w$.

### 3.1.2 Some algebraic geometry background and intuition

The adjunction formula states that for a non-singular complex curve $C$ embedded in a complex surface $X$ then

$$\Omega^1_C \cong \Omega^1_X|_C \otimes \nu_C$$

where $\nu_C$ is the holomorphic normal bundle of $C$, $\Omega^1_C$ is the holomorphic canonical line bundle of $C$ and $\Omega^1_X$ is the holomorphic canonical sheaf of $X$. Therefore, if a genus $g$ Seiberg-Witten curve $\Sigma(u) \subset \mathbb{P}^2$ was smooth and intersects $K_{\mathbb{P}^2}$ trivially, then $\Omega^1_{\mathbb{P}^2}|_{\Sigma(u)} \cong \mathcal{O}_{\Sigma(u)}$ and (3.2) implies that $\nu_{\Sigma(u)} \cong \Omega^1_{\Sigma(u)}$. Instead, $\Sigma(u)$ is singular and intersects non-trivially with $K_{\mathbb{P}^2}$ and we have from Bézout’s theorem that

$$\deg \nu_{\Sigma(u)} = \Sigma(u) \cdot \nu_{\Sigma(u)} = (\deg \Sigma(u))^2 = (g + 2)^2 > 2g - 2 = (g + 1)^2$$

where $N_{\Sigma(u)}$ denotes the normal bundle divisor, and so $\nu_{\Sigma(u)} \neq \Omega^1_{\Sigma(u)}$. From Riemann-Roch, the deformation space of $\Sigma(u)$ inside $\mathbb{P}^2$ has dimension

$$\dim \Gamma(\Sigma(u), \nu_{\Sigma(u)}) = \dim \Gamma(\Sigma(u), \Omega^1_{\Sigma(u)} \otimes \nu^*_{\Sigma(u)}) + \deg \nu_{\Sigma(u)} - g + 1$$

$$= 0 + (g + 2)^2 - g + 1 = g^2 + 3g + 5 > g$$

whereas the Seiberg-Witten family has dimension $q = \text{number of parameters} \{u_1, \ldots, u_g\}$. So the problem is that the deformation of $\Sigma(u)$ within the Seiberg-Witten family is more restrictive. In particular, $\Sigma(u)$ will always
pass through the point $[w : z : x] = [0 : 1 : 0]$ and $[w : z : x] = [1 : 0 : 0]$ for every value of $\{u_1, ..., u_g\}$, whereas if we are allowed to deform $\Sigma(u)$ freely it will not be fixed at these two points.

It suggests that the problem can be solved if we construct $S$ by performing a series of blow-ups starting from $\mathbb{P}^2$ until no such fix points exists for the Seiberg-Witten family and each curve $\Sigma(u)$ is non-singular. Conceptually, after each blow-up, the neighbourhood of $\Sigma(u)$ will become more restrictive and the dimension of its deformation space will be reduced. This can be seen as follows. Given a curve $C$ inside a surface $X$ and let $p \in X$. Then blowing up $p$ we have $\pi : \tilde{X} \to X$ and

$$\pi^* C = \tilde{C} + mE, \quad \pi^* C \cdot E = 0.$$ 

Where $\tilde{C}$ is the proper transform of $C$, $E$ is the exceptional divisor and $m$ is the multiplicity of the point $p$. In particular, $m = 0$ if $p \not\in C$, $m = 1$ if $p \in C$ is a non-singular point and $m > 1$ if $p \in C$ is a singular point of multiplicity $m$. The important thing for us is that

$$\deg \nu_{\tilde{C}} = \tilde{C} \cdot \tilde{C} = (\pi^* C - mE) \cdot (\pi^* C - mE) = C \cdot C - m^2 = \deg \nu_C - m^2.$$ 

Therefore, we have $\dim \Gamma(\tilde{C}, \nu_{\tilde{C}}) \leq \dim \Gamma(C, \nu_C)$ if $\deg \nu_{\tilde{C}} \leq \deg \nu_C$ by the application of Riemann-Roch.

It is also well-known what happens to the canonical class after the blow-up. We have

$$K_{\tilde{X}} = \pi^* K_X + E.$$ 

We will apply (3.3) successively to $K_{\mathbb{P}^2}$ as given in (3.1) and show that eventually, the canonical class will intersect the proper transform of the Seiberg-Witten curve $\Sigma(u)$ trivially. Then we define $S$ to be $\mathbb{P}^2$, after a series of blow-ups, excluding the canonical divisor. We will also check for consistency using (3.3) that the degree of $\nu_{\Sigma(u)}$ drops to $2g - 2$. In the end, we conclude that the moduli space $\mathcal{B}$ of $J$-transversal genus $g$ curves in the resulting foliated symplectic surface $(S, \Omega_S, F)$ coincides with the family of smooth Seiberg-Witten curves.

### 3.1.3 Constructing $S$. Part 1: Blowing up $[w : z : x] = [1 : 0 : 0]$

Let us start with considering the blow-up starting from $[w : z : x] = [1 : 0 : 0]$. We consider the open set $U_w := \{w \neq 0\} = \mathbb{A}^2 \subset \mathbb{P}^2$. Set $w = 1$, the local coordinates on $U_w$ are $(z, x)$ and we have

$$\Sigma(u) \cap U_w = \{(z, x) \in U_w \mid x^g - z^{g+1} - u_2 x^2 z^{g-1} - ... - u_i x^{g+1} + x^{g+2} = 0\} \subset U_w.$$ 

Let $\tilde{\mathbb{P}}^2 \to \mathbb{P}^2$ be the blow-up of $\mathbb{P}^2$ at $[w : z : x] = [1 : 0 : 0]$. Locally on $U_w$ we write this as $\tilde{U}_w \to U_w$ where

$$\tilde{U}_w = \{(z, x, [\tilde{z} : \tilde{x}]) \in U_w \times \mathbb{P}^1 \mid \tilde{z} \tilde{x} = 0\} \subset U_w \times \mathbb{P}^1.$$ 

Let $\tilde{\Sigma}_1(u)$ be the proper transform of $\Sigma(u)$. Consider the open subset $U_{w,1} := \{\tilde{z} \neq 0\} \subset \tilde{U}_w$, i.e. we set $\tilde{z} = 1$, so $x = \tilde{x}$ and we can take $(z, x, 1) = (z, x, \tilde{x})$ to be the local coordinates on $U_{w,1}$. Then

$$\tilde{\Sigma}_1(u) \cap U_{w,1} = \{(z_1, x_1) \in U_{w,1} \mid x_1^g - z_1 - u_2 x_1^2 z_1 - ... - u_i x_1^{g+1} z_1 + x_1^{g+2} z_1^{g+1} = 0\} \subset U_{w,1}.$$ 

We can see that for any choices of $u$ the curve $\tilde{\Sigma}_1(u)$ always passes through the point $(z_1, x_1) = (0, 0)$. We can check that there is no such basepoint on the other open set $V_{w,1} := \{\tilde{x} \neq 0\} \subset \tilde{U}_w$. This confirms that $\Sigma(u)$ intersects $[w : z : x] = [1 : 0 : 0]$ tangentially to $H_x$ as illustrated by Figure 3.1.1. To continue we need to repeat the process by blowing up again at $(z_1, x_1) = (0, 0)$. Let us remark that the blow-up has removed the singular point and $\tilde{\Sigma}_1(u)$ is a non-singular curve. Let $E_{w,1} := \{z = 0, x = 0\} \subset \tilde{U}_w$ be the exceptional divisor. Using (3.4) we have found that

$$K_{\tilde{\mathbb{P}}^2} = \pi^* K_{\mathbb{P}^2} + E_{w,1} = \pi^*(-H_w - 2H_x) + E_{w,1} = -H_w - 2(H_x + E_{w,1}) + E_{w,1} = -H_w - 2H_x - E_{w,1},$$

therefore $\tilde{\Sigma}_1(u)$ still intersects $K_{\tilde{\mathbb{P}}^2}$ non-trivially. Moreover, $\deg N_{\tilde{\Sigma}_1(u)} = \deg N_{\Sigma(u)} - g^2$. Since the remaining blow-ups will occur on non-singular points, the degree of normal bundle will always go down by 1 for each blow-up.

Let $\tilde{\mathbb{P}}^2 \to \tilde{\mathbb{P}}^2$ be the blow-up of $\tilde{\mathbb{P}}^2$ at $(z_1, x_1) = (0, 0) \in U_{w,1} \subset \tilde{\mathbb{P}}^2$. Locally on $U_{w,1}$ we write this as $\tilde{U}_{w,1} \to U_{w,1}$ where

$$\tilde{U}_{w,1} = \{(z_1, x_1, [\tilde{z}_1, \tilde{x}_1]) \in U_{w,1} \times \mathbb{P}^1 \mid \tilde{z}_1 \tilde{x}_1 = 0\} \subset U_{w,1} \times \mathbb{P}^1.$$ 

Let $\tilde{\Sigma}_2(u)$ be the proper transform of $\tilde{\Sigma}_1(u)$. Consider the open subset $U_{w,2} := \{\tilde{z}_1 \neq 0\} \subset \tilde{U}_{w,1}$ with coordinates $(z_2, x_2) := (\tilde{z}_1, x_1)$. For any choice of $u$ the curve $\tilde{\Sigma}_2(u)$ always pass the point $(z_2, x_2) = (0, 0)$. We can check
Summary of the construction of the foliated symplectic surface \((S, \Omega_S, \mathcal{F})\). We notice that \(\Omega_S\) is holomorphic on \(E_{z,4}\) and \(E_{w,g+3}\) which \(\Sigma(u)\) intersects with transversely.

that there is no such fixed point on the other open set \(V_{w,1} := \{ \tilde{z}_1 \neq 0 \} \). We repeat this process \(g\) times. In more detail, for \(i = 1, \ldots, g\), we let \(\tilde{P}_{i+1}^2 \to \tilde{P}_i^2\) be the blow-up of \(\tilde{P}_i^2\) at \((z_i, x_i) = (0, 0) \in U_{w,i} \subseteq \tilde{P}_i^2\). Locally on \(U_{w,i}\) we write this as \(\tilde{U}_{w,i} \to U_{w,i}\). Let \(\tilde{\Sigma}_{i+1}(u)\) be the proper transform of \(\tilde{\Sigma}(u)\). Set \(U_{w,i+1} := \{ \tilde{x}_i \neq 0 \} \subset \tilde{U}_{w,i}\) with coordinates \((z_{i+1}, x_{i+1}) := (\tilde{z}_i, x_i)\). We find that

\[
\tilde{\Sigma}_{g+1}(u) \cap U_{w,g+1} = \left\{ (z_{g+1}, x_{g+1}) \in U_{w,g+1} \mid 1 - z_{g+1} - u_1 x_{g+1}^2 z_{g+1} + \ldots - u_1 x_{g+1}^{g+1} + x_{g+1}^{2g+2} z_{g+1}^2 = 0 \right\}.
\]

On the other hand, repeated application of (3.4) gives

\[
K_{\tilde{P}_g^2} = -H_w - 2H_z - E_{w,1} - 2 \sum_{i=1}^g E_{w,i+1}
\]

where \(E_{w,i+1} := \{ z_i = 0, x_i = 0 \} \subset \tilde{U}_{w,i}\) are exceptional divisors. This time we observe that \(\tilde{\Sigma}_{g+1}(u)\) passes through the point \((z_{g+1}, x_{g+1}) = (1, 0)\) for any choice of \(u\). Let us define the new coordinates by \((z_{g+1}' = z_{g+1} - 1, x_{g+1}') := (z_{g+1} - 1, x_{g+1})\). We continue by letting \(\tilde{P}_{g+2}^2 \to \tilde{P}_{g+1}^2\) to be the blow-up at \((z_{g+1}', x_{g+1}') = (0, 0)\). Locally, we write this as \(\tilde{U}_{w,g+1} \to U_{w,g+1}\) where

\[
\tilde{U}_{w,g+1} = \left\{ (z_{g+1}', x_{g+1}', [z_{g+1}'^2 x_{g+1}']) \in U_{w,g+1} \times \mathbb{P}^1 \mid z_{g+1}' x_{g+1}' - 1 = 0 \right\} \subset U_{w,g+1} \times \mathbb{P}^1.
\]

Let \(\tilde{\Sigma}_{g+2}(u)\) be the proper transform of \(\tilde{\Sigma}_{g+1}(u)\) and let \(E_{w,g+2} := \{ z_{g+1}' = 0, x_{g+1}' = 0 \} \subset \tilde{U}_{w,g+1}\) be the exceptional divisor. Consider the open set \(U_{w,g+2} := \{ x_{g+1}' \neq 0 \} \subset \tilde{U}_{w,g+1}\) and let the local coordinates
be \((z_{g+2}, x_{g+2}) := (z'_{g+1}, x'_{g+1})\). For any choices of \(u\), the curve \(\Sigma_g(u)\) always passes through the point \((z_{g+2}, x_{g+2}) = (0, 0)\). Blow up at the point \((z_{g+2}, x_{g+2}) = (0, 0)\) to get \(\mathbb{P}^2_{g+3} \to \mathbb{P}^2_{g+2}\). Let \(\Sigma_{g+3}(u)\) be the proper transform of \(\Sigma_{g+2}(u)\). We can check that we no longer have any fixed points. Consider the open set \(U_{w,g+3} := \{(x_{g+3} \neq 0) \subset U_{w,g+2}\) and let \((z_{g+3}, x_{g+3}) := (z_{g+2}, x_{g+2})\) be the local coordinates. Then

\[
\Sigma_{g+3}(u) \cap U_{w,g+3} = \left\{ (z_{g+3}, x_{g+3}) \in U_{w,g+3} \mid -z_{g+3} - (u_g + u_{g-1} x_{g+3}) + \ldots + u_1 x_{g+3}^{-1} + x_{g+3}^2 (x_{g+3}^2 z_{g+3} + 1) + x_{g+3}^2 (x_{g+3}^2 z_{g+3} + 1) = 0 \right\}
\]

intersects the exceptional divisor \(E_{w,g+3} := \{ z_{g+3} = 0, x_{g+3} = 0 \} \subset U_{w,g+2}\) at \((z_{g+3}, x_{g+3}) = (0, 0)\) which varies with \(u\). Using (3.4) we find that the canonical divisor of \(\mathbb{P}^2_{g+3}\) is

\[
K_{\mathbb{P}^2_{g+3}} = -H_w - 2H_x - E_{w,1} - \sum_{i=2}^{g+1} E_{w,i} - E_{w,g+2}.
\]

Let \(U_z := \{ z \neq 0 \} \subset \mathbb{P}^2_{g+3}\) be an open set with coordinates \((w, x)\). We notice that \(\Sigma_{g+3}(u) \subset \mathbb{P}^2_{g+3}\) only intersects \(K_{\mathbb{P}^2_{g+3}}\) on \(U_z\) at \((w, x) = 0\). This is the point \([w : z : x] = [0 : 1 : 0] \in \mathbb{P}^2\) if we blow-down \(\mathbb{P}^2_{g+3}\) to \(\mathbb{P}^2\). So the next step is to perform another series of blow-ups starting from \((w, x) = (0, 0)\).

### 3.1.4 Constructing S. Part 2: Blowing up \([w : z : x] = [0 : 1 : 0]\)

On the open set \(U_z = \{ z \neq 0 \} \subset \mathbb{P}^2_{g+3}\) we set \(z = 1\) and it follows that

\[
\Sigma_{g+3}(u) \cap \mathbb{P}^2_{g+3} = \{(w, x) \in U_z \mid w^2 x^9 - w(1 + u_g x^2 + \ldots + u_1 x^{g+1}) + x^{g+2} = 0 \}.
\]

Let \(\mathbb{P}^2_{g+3,1} \to \mathbb{P}^2_{g+3}\) be the blow-up of \(\mathbb{P}^2_{g+3}\) at \((w, x) = (0, 0) \in U_z\). Locally on \(U_z\) we write this as \(U \to U_z\) where

\[
\tilde{U}_z = \{(w, x, [\tilde{u}, \tilde{x}]) \in U_z \times \mathbb{P}^1 \mid w \tilde{w} - \tilde{w} \tilde{x} = 0 \}.
\]

Let \(\tilde{\Sigma}_{g+3,1}(u)\) be the proper transform of \(\tilde{\Sigma}_{g+3}(u)\) and \(E_{z,1} := \{ w = 0, x = 0 \} \subset \tilde{U}_z\) be the exceptional divisor. Consider the open subset \(U_{z,1} := \{ \tilde{x} \neq 0 \} \subset \tilde{U}_z\) with coordinates \((w_1, x_1) := (\tilde{w}, \tilde{x})\). For any choice of \(u\), the curve \(\tilde{\Sigma}_{g+3,1}(u)\) passes through the point \((w_1, x_1) = (0, 0)\). This confirms that \(\Sigma(u)\) intersects \([w : z : x] = [0 : 1 : 0]\) tangentially to \(H_x\) as illustrated by Figure 3.1.1. We repeat this process \(g + 2\) times. In more detail, for \(i = 1, \ldots, g + 1\), we let \(\mathbb{P}^2_{g+3,i+1} \to \mathbb{P}^2_{g+3,i}\) be the blow-up at \((w_i, x_i) = (0, 0) \in U_{z,i} \subset \mathbb{P}^2_{g+3,i}\). Locally on \(U_{z,i}\) we write this as \(U_{z,i} \to U_{z,i}\). Let \(\tilde{\Sigma}_{g+3,i+1}(u)\) be the proper transform of \(\tilde{\Sigma}_{g+3,i}(u)\) and let \(E_{z,i+1} := \{ w_i = 0, x_i = 0 \} \subset \tilde{U}_{z,i}\). Set \(U_{z,i+1} := \{ \tilde{x}_i \neq 0 \} \subset \tilde{U}_{z,i}\) with coordinates \((w_{i+1}, x_{i+1}) := (\tilde{w}_i, \tilde{x}_i)\). Then we find that

\[
\tilde{\Sigma}_{g+3,g+2}(u) \cap U_{z,g+2} = \{(w_{g+2}, x_{g+2}) \in U_{z,g+2} \mid w_{g+2} x_{g+2}^2 - w_{g+2} (1 + u_g x_{g+2}^2 + \ldots + u_1 x_{g+1}^2) + 1 = 0 \}.
\]

Therefore \(\tilde{\Sigma}_{g+3,g+2}(u)\) passes through the point \((w_{g+2}, x_{g+2}) = (1, 0)\) for all \(u\). We define new coordinates \((w'_{g+2}, x'_{g+2}) := (w_{g+2} - 1, x_{g+2})\) and continue by letting \(\mathbb{P}^2_{g+3,g+3} \to \tilde{\mathbb{P}^2}_{g+3,g+2}\) be the blow-up at \((w'_{g+2}, x'_{g+2}) = (0, 0)\). Locally, we write this as \(U_{z,g+2} \to U_{z,g+2}\) where

\[
\tilde{U}_{z,g+2} = \{(w'_{g+2}, x'_{g+2}, [w'_{g+2}, x'_{g+2}]) \in U_{z,g+2} \times \mathbb{P}^1 \mid w'_{g+2} x'_{g+2}^2 - w'_{g+2} x'_{g+2} = 0 \} \subset U_{z,g+2} \times \mathbb{P}^1.
\]

Let \(\tilde{\Sigma}_{g+3,g+3}(u)\) be the proper transform of \(\tilde{\Sigma}_{g+3,g+2}(u)\) and let \(E_{z,g+3} := \{ w_{g+2} = 0, x_{g+2} = 0 \} \subset \tilde{U}_{z,g+2}\) be the exceptional divisor. Consider the open set \(U_{z,g+3} := \{ \tilde{x}_{g+2} \neq 0 \} \subset \tilde{U}_{z,g+2}\) and let the local coordinates be \((w_{g+3}, x_{g+3}) := (\tilde{w}_{g+2}, \tilde{x}_{g+2})\). For any choice of \(u\), the curve \(\tilde{\Sigma}_{g+3,g+3}(u)\) always passes through the point \((w_{g+3}, x_{g+3}) = (0, 0)\). Blow up at the point \((w_{g+3}, x_{g+3}) = (0, 0)\) to get \(\mathbb{P}^2_{g+3,g+4} \to \tilde{\mathbb{P}^2}_{g+3,g+3}\). Let \(\tilde{\Sigma}_{g+3,g+4}(u)\) be the proper transform of \(\tilde{\Sigma}_{g+3,g+3}(u)\). We can check that we no longer have any basepoint. Consider the open set \(U_{z,g+4} := \{ \tilde{x}_{g+3} \neq 0 \} \subset \tilde{U}_{z,g+3}\) and let \((w_{g+4}, x_{g+4}) := (\tilde{w}_{g+3}, x_{g+3})\) be the local coordinates. Then

\[
\tilde{\Sigma}_{g+3,g+4}(u) \cap U_{z,g+4} = \{(w_{g+4}, x_{g+4}) \in U_{z,g+4} \mid (x_{g+4}^2 w_{g+4}^4 + 1)^2 x_{g+4}^2 w_{g+4} - w_{g+4} = 0 \} \subset U_{z,g+4} \times \mathbb{P}^1.
\]

intersects the exceptional divisor \(E_{z,g+4} := \{ w_{g+4} = 0, x_{g+4} = 0 \} \subset \tilde{U}_{z,g+3}\) at \((w_{g+4}, x_{g+4}) = (0, 0)\) which varies with \(u\).
Finally, using (3.4) we find that the canonical divisor of $\mathbb{P}^2_{g+3,g+4}$ is

$$K_{g+3,g+4} = -H_w - 2H_x - E_{w,1} - 2 \sum_{i=2}^{g+1} E_{w,i} - E_{w,g+2} - 2 \sum_{i=1}^{g+2} E_{z,i} - E_{z,g+3}.$$ 

Evidently, the curve $\Sigma_{g+3,g+4}(u)$ intersects $K_{g+3,g+4}$ trivially and therefore, we have $\nu_{\Sigma_{g+3,g+4}} \simeq \Omega^1_{\Sigma_{g+3,g+4}}$ by (3.2). In particular, the moduli space now has the correct dimension \( \dim \Gamma(\Sigma_{g+3,g+4}(u), \nu_{\Sigma_{g+3,g+4}(u)}) = \dim \Gamma(\Sigma_{g+3,g+4}(u), \Omega^1_{\Sigma_{g+3,g+4}(u)}) = g. \)

We can check the consistency by calculating the degree of $\nu_{\Sigma_{g+3,g+4}(u)}$ using (3.3):

$$\deg \nu_{\Sigma_{g+3,g+4}(u)} = \deg \nu_{\Sigma(u)} - g^2 - (g + 2) - (g + 4) = (g + 2)^2 - (g^2 + 2g + 6) = 2g - 2.$$ 

### 3.1.5 Summary

The Figure 3.1.2 assists the visualization of this construction. We define $S := \mathbb{P}^2_{g+3,g+4} \setminus K_{g+3,g+4}$. We take $\Sigma_{g+3,g+4}(u)$ to be the embedding of the Seiberg-Witten curve $\Sigma(u)$ in $S$ which we will simply denote by $\Sigma(u) \subset S$ from now on. It is clear that $C^* \times C$ is an open dense subset of $S$. The symplectic form is $\Omega_S := \Omega(w/z) \wedge d(\frac{w}{z})$ where we have extended the domain of functions $\frac{w}{z}$ and $\frac{w}{x}$ from $\mathbb{P}^2$ to $S \subset \mathbb{P}^2_{g+3,g+4}$ in the obvious way. The foliation $\mathcal{F}$ is given by $\frac{w}{z} = \text{const.}$ On the open set $U_{w,g+3}$, the foliation $\mathcal{F}$ is given in local coordinates $(z_{g+3}, x_{g+3})$ by

$$(z_{g+3} x_{g+3}^2 + 1) x_{g+3}^{g+1} = \text{const.}$$

We find that $E_{w,g+3} \cap U_{w,g+3} = \{ x_{g+3} = 0 \}$ is a leaf of the foliation with $\text{const} = 0$ and so $\Sigma(u)$ is transverse to the foliation at the intersection $\Sigma(u) \cap E_{w,g+3} = \{ (z_{g+3}, x_{g+3}) = (-u_g, 0) \}$. Similarly, on the open set $U_{x,g+4}$ for foliation $\mathcal{F}$ is given in local coordinates $(w_{g+4}, x_{g+4})$ by

$$(w_{g+4} x_{g+4}^2 + 1) x_{g+4}^{g+1} = \text{const.}$$

We find that $E_{x,g+4} \cap U_{x,g+4} = \{ x_{g+4} = 0 \}$ is a leaf of the foliation with $\text{const} = 0$ and so $\Sigma(u)$ is transverse to the foliation at the intersection $\Sigma(u) \cap E_{x,g+4} = \{ (w_{g+4}, x_{g+4}) = (-u_g, 0) \}$.

It follows that all ramification points of $\Sigma(u) \subset S$ are contained inside the dense subset $C^* \times C \subset S$.

### 3.2 From the Seiberg-Witten Family of Curves to Airy Structures

Let us consider the genus $g$ family $\mathcal{B}$ of smooth Seiberg-Witten curves $\Sigma(u)$ embedded in $(S, \Omega_S, \mathcal{F})$ as constructed in the last section. Since all ramification points of $\Sigma(u)$ are contained inside $C^* \times C \subset S \to \mathbb{P}^2$, for all practical purposes we can work exclusively in this subset and set $x = 1$. We now have $\Omega_S = \frac{w}{z} \wedge dz$ and $\Sigma(u)$ is defined by the algebraic equation $w + \frac{1}{w} = P(z; u)$. Throughout this section, we will denote by

$$z_i(u), \quad i = 1, \ldots, g$$

the roots of $P(z; u) = 0$ and we will fix the reference point to be $[\Sigma_0] := [\Sigma(w_0)] \in \mathcal{B}$.

We begin in Section 3.2.1 by locating the ramification points $\{ r_{\alpha \in \text{Ram}} \}$ of $\Sigma(u)$ and write down the local parameterization of each $r_\alpha$. Recall that the image $\gamma(\Sigma_0)$ of $\Sigma_0$ in $\text{Discs}_{\text{Ram}}$ needs to take the form $(x_\alpha = x_\alpha^z, y_\alpha = z_\alpha), \alpha \in \text{Ram}$ for the image of the embedding $\Phi_{\Sigma_0} : B_{\Sigma_0} \to G_{\Sigma_0}$ to satisfy the $\text{Ram}$ product residue constraints (see Proposition 2.5.38). Therefore, in Section 3.2.2 we explicitly find the $(\mathcal{F}, \Omega_S)$-local coordinates transformation which brings $\gamma(\Sigma_0)$ into the needed form. This gives us a collection of $(\mathcal{F}, \Omega_S)$-charts $\mathcal{U}_{\text{Ram}}$. Then in Section 3.2.3 we will also explain how the parameters $\{ r_{\alpha \in \text{Ram}} \}, \{ M_{\alpha \in \text{Ram}} \}$ and an open neighbourhood $B_{\Sigma_0}$ of $\Sigma_0 \in \mathcal{B}$ can be chosen. Now that $\{ r_{\alpha \in \text{Ram}} \}, \{ M_{\alpha \in \text{Ram}} \}, \mathcal{U}_{\text{Ram}}$ and $B_{\Sigma_0}$ has been selected, we are going to write down the embedding $\gamma : B_{\Sigma_0} \hookrightarrow \text{Discs}_{\text{Ram}}(\Sigma_0)$ follows by $\text{Discs}_{\text{Ram}}(\Sigma_0) \hookrightarrow W_{\text{Ram}}(\Sigma_0)$ as given in Section 3.2.4 and the embedding $B_{\Sigma_0} \hookrightarrow G_{\Sigma_0}$ in Section 3.2.5 respectively. These two embeddings will be compared, giving a proof of Proposition 2.5.38 in the specific example of the Seiberg-Witten family of curves.
3.2.1 Ramification points and local parameterization of Seiberg-Witten curves

Ramification points of $\Sigma_0$ are

$$\text{Ram} = \left\{ r_{i\pm} = \left( w = -P(z_i(u_0); u_0) \pm \frac{\sqrt{P(z_i(u_0); u_0)^2 - 4}}{2}, z = z_i(u_0) \right) \mid i = 1, \ldots, g \right\}. \quad (3.7)$$

Let us choose the local coordinates $(w_{i\pm}, z_{i\pm})$ of $S$ around $r_{i\pm}$ to be

$$(w_{i\pm}, z_{i\pm}) = \left( w + \frac{1}{w} + \frac{z}{w - 1}, \frac{z}{w - 1} \right). \quad (3.8)$$

We have $\Omega_S = dw_{i\pm} \wedge dz_{i\pm}$ and the foliation is $w_{i\pm} = \text{const}$. Of course, this is not a unique choice, alternatively we can also use $(\log w, z)$ but it will be harder to write down the standard local coordinates. Given a curve $[\Sigma(u)] \in \mathcal{B}_{\Sigma_0}$, we find a standard local coordinates $\eta_{i\pm}^2 := P(z; u) - P(z_i(u); u) = \frac{1}{2} P''(z_i(u); u)(z - z_i(u))^2 + \ldots$ of $\Sigma(u)$ around $r_{i\pm}(\Sigma(u))$. The parameterization of $\Sigma(u)$ is given in the same $(w_{i\pm}, z_{i\pm})$ coordinates of $S$ by

$$t_{i\pm}(\Sigma(u)) = \left( w_{i\pm} = \eta_{i\pm}^2 + P(z_i(u); u), z_{i\pm} = \pm \frac{z(\eta_{i\pm}; u)}{\sqrt{(\eta_{i\pm}^2 + P(z_i(u); u))^2 - 4}} \right). \quad (3.9)$$

Where $z(\eta_{i\pm}; u) = z_i(u) + \left( \frac{\eta_{i\pm}^2}{P''(z_i(u); u)} \right)^{\frac{1}{2}} \eta_{i\pm} + \ldots$ is the inverse of $\eta_{i\pm}^2 = P(z; u) - P(z_i(u); u)$ for $z \approx z_i(u)$ or $\eta_{i\pm} \approx 0$. When $u = u_0$ the parameterization of $\Sigma_0$ near $r_{i\pm}(\Sigma_0)$ using the standard local coordinates $\eta_{i\pm}$ is given in the $(w_{i\pm}, z_{i\pm})$ coordinates by

$$t_{i\pm}(\Sigma_0) = \left( w_{i\pm} = \eta_{i\pm}^2 + P(z_i(u_0); u_0), z_{i\pm} = \pm \frac{z(\eta_{i\pm}; u_0)}{\sqrt{(\eta_{i\pm}^2 + P(z_i(u_0); u_0))^2 - 4}} \right). \quad (3.10)$$

The problem is that in $(w_{i\pm}, z_{i\pm})$ local coordinates $t_{i\pm}(\Sigma_0)$ does not equal to $(w_{i\pm} = \eta_{i\pm}^2, z_{i\pm} = \eta_{i\pm})$.

3.2.2 Choosing the $(\mathcal{F}, \Omega_S)$-local coordinates

Lemma 2.1.9 tells us that we can transform into a new local coordinates

$$(w_{i\pm}, z_{i\pm}) = \left( F_{i\pm}(w_{i\pm}), \frac{z_{i\pm}}{F'_{i\pm}(w_{i\pm})} - G'_{i\pm}(w_{i\pm}) \right) \quad (3.11)$$

of $S$ around $r_{i\pm}(\Sigma_0)$ such that $\Omega_S = \tilde{w}_{i\pm} \wedge \tilde{z}_{i\pm}$ and the foliation is $\tilde{w}_{i\pm} = \text{const}$ and $t_{i\pm}(\Sigma_0) = (\tilde{w}_{i\pm} = \tilde{\eta}_{i\pm}^2, \tilde{z}_{i\pm} = \tilde{\eta}_{i\pm})$ where the new standard local coordinates $\tilde{\eta}_{i\pm}$ is given by $\tilde{\eta}_{i\pm}^2 := F_{i\pm}(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0))$. Comparing (2.3) with (3.10) determines what function $F_{i\pm}$ and $G_{i\pm}$ have to be:

$$F_{i\pm}^{-1}(0) = P(z_i(u_0); u_0) \quad (3.12)$$

$$F_{i\pm}'(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0)) \left( (F_{i\pm}(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0))^{1/2} + G_{i\pm}'(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0)) \right) = \pm \frac{z(\eta_{i\pm}; u_0)}{\sqrt{(\eta_{i\pm}^2 + P(z_i(u_0); u_0))^2 - 4}}. \quad (3.13)$$

We separate $z(\eta_{i\pm}; u_0)$ into the sum of its odd and even components $z(\eta_{i\pm}; u_0) = z_{\text{odd}}(\eta_{i\pm}; u_0) + z_{\text{even}}(\eta_{i\pm}; u_0)$ where

$$z_{\text{odd}}(\eta_{i\pm}; u_0) := \frac{z(+\eta_{i\pm}; u_0) - z(-\eta_{i\pm}; u_0)}{2}, \quad z_{\text{even}}(\eta_{i\pm}; u_0) := \frac{z(+\eta_{i\pm}; u_0) + z(-\eta_{i\pm}; u_0)}{2}.$$ 

Comparing the odd components on both sides of (3.13), we have

$$\left( \frac{1}{2\eta_{i\pm}^2} \right) (F_{i\pm}(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0)))^{1/2} \frac{d}{d\eta_{i\pm}} F_{i\pm}(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0)) = \pm \frac{z_{\text{odd}}(\eta_{i\pm}; u_0)}{\sqrt{(\eta_{i\pm}^2 + P(z_i(u_0); u_0))^2 - 4}}$$

$$\quad \Rightarrow \frac{1}{3} \frac{d}{d\eta_{i\pm}} (F_{i\pm}(\eta_{i\pm}^2 + F_{i\pm}^{-1}(0)))^{3/2} = \pm \frac{\eta_{i\pm} z_{\text{odd}}(\eta_{i\pm}; u_0)}{\sqrt{(\eta_{i\pm}^2 + P(z_i(u_0); u_0))^2 - 4}}.$$
Next, we compare the even components on both sides of (3.13). We have

\[ \text{Substituting the expression for } F \text{ of (3.12) we can write down the coordinates transformation from (log } w, z \text{) to (} w_{±}, \bar{z}_{±} \text{) in terms of the function } F_{±} \text{ we have found in (3.15):} \]

\[ F_{±}(w_{±}) = \left( 3 \int_{0}^{w_{±} - P(z_{i}(u_{0}); u_{0})} \frac{\tau z_{odd}(\tau; u_{0})}{(\tau^{2} + P(z_{i}(u_{0}); u_{0}))^{2} - 4} d\tau. \right)^{2/3} \]

With our choice of the third-root we have \( F_{±} = F_{i-} \), similar to how we have \( w_{i+} = w + \frac{1}{w} = w_{i-} \). Using the expansion \( z(η_{i±}; u) = z_{i}(u) + \left( \frac{2}{P_{n}(z_{i}(u); u)} \right)^{1/2} + ... \), the expansion of \( F_{±}(w_{±}) \) around the ramification point \( r_{±} \) is given by

\[ F_{±}(w_{±}) = (w_{±} - P(z_{i}(u_{0}); u_{0})) \left( \frac{2}{P_{n}(z_{i}(u_{0}); u_{0})} \right)^{1/2} + O \left( (w_{±} - P(z_{i}(u_{0}); u_{0}))^{2} \right) \]

Next, we compare the even components on both sides of (3.13). We have

\[ F_{±}(η_{i±}^{2} + F_{i±}^{-1}(0)) G'_{±}(η_{i±}^{2} + F_{i±}^{-1}(0)) = \pm \frac{z_{even}(η_{i±}; u_{0})}{\sqrt{(η_{i±}^{2} + P(z_{i}(u_{0}); u_{0}))^{2} - 4}} \]

Substituting the expression for \( F_{±} \) from (3.15) we have

\[ G'_{±}(w_{±}) = \frac{z_{even}(\sqrt{w_{±} - P(z_{i}(u_{0}); u_{0}); u_{0}})}{z_{odd}(\sqrt{w_{±} - P(z_{i}(u_{0}); u_{0}); u_{0}})} (F_{±}(w_{±}))^{1/2}. \]

Finally, using (3.8) and (3.11) we can write down the coordinates transformation from (log \( w, z \)) to (\( w_{i±}, \bar{z}_{i±} \)) in terms of the function \( F_{±} \) we have found in (3.15):

\[ \bar{w}_{±} = F_{±} \left( w + \frac{1}{w} \right) \]

\[ \bar{z}_{±} = \left( \frac{z - z_{even}(\sqrt{w + \frac{1}{w} - P(z_{i}(u_{0}); u_{0}); u_{0}})}{z_{odd}(\sqrt{w + \frac{1}{w} - P(z_{i}(u_{0}); u_{0}); u_{0}})} \right) \left( F_{±} \left( w + \frac{1}{w} \right) \right)^{1/2}. \]

Using the standard local coordinate

\[ \bar{η}_{i±} := \sqrt{F_{±}(η_{i±}^{2} + P(z_{i}(u); u)) - F_{±}(P(z_{i}(u_{0}); u_{0}))} \]

corresponding to the local coordinates (\( \bar{w}_{±}, \bar{z}_{±} \)), we find that \( t_{±}(\Sigma(u)) \) as given in (3.9) becomes

\[ t_{±}(\Sigma(u)) = \left( \bar{w}_{±} = \bar{η}_{i±}^{2} + F_{±}(P(z_{i}(u); u)), \bar{z}_{±} = \frac{z \left( \sqrt{F_{±}^{-1}(\bar{η}_{i±}^{2} + F_{±}(P(z_{i}(u); u))) - P(z_{i}(u); u))} \sqrt{\bar{η}_{i±}^{2} + F_{±}(P(z_{i}(u); u))} \right)}{z_{odd} \left( \sqrt{F_{±}^{-1}(\bar{η}_{i±}^{2} + F_{±}(P(z_{i}(u); u))) - P(z_{i}(u); u))} \right)} \]

\[ = \sum_{k=0}^{∞} b_{i±,k}(\Sigma) \bar{η}_{i±}^{k} \in Discs^{M_{i±}} \]
When \( u = u_0 \), we have \( F_{i,\pm}(P(z_i(u);u)) = 0 \) and evidently

\[
\ell_{i,\pm}(\Sigma(u = u_0)) = \ell_{i,\pm}(\Sigma_0) = (\bar{w}_{i,\pm} = \bar{\eta}_{i,\pm}^2, \bar{z}_{i,\pm} = \bar{\eta}_{i,\pm}) \in Discs^{M_{i,\pm}}
\]
as expected. We note that \( \bar{z}_{i,\pm} \) is a well-defined holomorphic function of \( \bar{\eta}_{i,\pm} \) for all \( |\bar{\eta}_{i,\pm}| < M_{i,\pm} \) (for some constant \( M_{i,\pm} \) which we are going to discuss soon) and for all \( u \) close to \( u_0 \) (or \( \Sigma \in B_{\Sigma_0} \) close to \( \Sigma_0 \)) despite all of appearance of square-roots. This is because \( z_{\text{odd}} \) factors are \( \sim \sqrt{\bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u)) (1 + O(\bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u))))} \) as \( F_{i,\pm}^{-1}(\bar{w}_{i,\pm}) = P(z_i(u_0);u_0) + O(\bar{w}_{i,\pm}) \) and the factor \( \sqrt{\bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u))} \) cancels with the same factor in the numerator. On the other hand, \( z_{\text{even}} \) is free of square-roots because it only contains the even power terms. Lastly, \( F_{i,\pm}^{-1}(\bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u))) - P(z_i(u);u) \) vanishes when \( \bar{\eta}_{i,\pm}^2 = 0 \) and so it is \( \sim \bar{\eta}_{i,\pm}^2 (1 + O(\bar{\eta}_{i,\pm}^2)) \).

### 3.2.3 Choosing \( \{\epsilon_{i,\pm}\}, \{M_{i,\pm}\}, U_{\text{Ram}} \) and \( \mathcal{B}_{\Sigma_0} \)

So far we have not chosen explicitly what \( \{\epsilon_{i,\pm}\}, \{M_{i,\pm}\}, U_{\text{Ram}} := \{(U_{i,\pm}, \bar{w}_{i,\pm}, \bar{z}_{i,\pm})\} \) and \( \mathcal{B}_{\Sigma_0} \) are. As we have mentioned, Condition 2.5.2 merely gave us a list of sufficient conditions on how to choose \( \{\epsilon_{i,\pm}\}, \{M_{i,\pm}\}, U_{\text{Ram}} \), and \( \mathcal{B}_{\Sigma_0} \). It is often easier to deal with the situation on a case-by-case basis and therefore in the following we will not refer ourselves to Condition 2.5.2. From (3.16) we can see that \( F_{i,\pm}^{-1}(P(z_i(u_0);u_0)) \) vanishes when \( |\bar{w}_{i,\pm} - P(z_i(u_0);u_0)| < R_{i,\pm} \).

Let us choose

\[
U_{i,\pm} := \left\{ (w, z) \in C \times C \subset \mathbb{P}^2 \mid \left| w + \frac{1}{w} - P(z_i(u_0);u_0) \right| < R_{i,\pm} \right\} \ni r_{i,\pm}(\Sigma_0).
\]

In particular, the open set \( U_{i,\pm} \) does not contain the ramification points of \( z : \Sigma_0 \to \mathbb{P}^1 \) given by \( w + \frac{1}{w} = \pm 2 \) as \( F_{i,\pm}(\bar{w}_{i,\pm}) \) is singular at \( \bar{w}_{i,\pm} = \pm \frac{1}{\sqrt{w}} \). Let \( \bar{R}_{i,\pm} \) be such that \( F_{i,\pm}^{-1}(\bar{w}_{i,\pm}) \in U_{i,\pm} \) for all \( |\bar{w}_{i,\pm}| < \bar{R}_{i,\pm} \).

Choose \( \epsilon_{i,\pm}, M_{i,\pm} \) to be any real numbers such that \( 0 < \epsilon_{i,\pm} < M_{i,\pm} \) and \( M_{i,\pm} + \epsilon_{i,\pm} < \bar{R}_{i,\pm} \). Finally, we let \( \mathcal{B}_{\Sigma_0} \) to be any contractible space such that

\[
\mathcal{B}_{\Sigma_0} \subset \{ (\Sigma(u)) \in \mathcal{B} \mid |F_{i,\pm}(P(z_i(u);u))| < \epsilon_{i,\pm}, \forall i = 1, \ldots, g \}.
\]

It is clear that \( \Sigma_0 \in \mathcal{B}_{\Sigma_0} \) since \( F_{i,\pm}(P(z_i(u_0);u_0)) = 0 \). Finally, we note that for any \( \Sigma \in \mathcal{B}_{\Sigma_0} \) we have \( \bar{w}_{i,\pm} = \bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u)) \) and so \( |\bar{w}_{i,\pm}| < |\bar{\eta}_{i,\pm}| + |F_{i,\pm}(P(z_i(u);u))| = M_{i,\pm}^2 + \epsilon_{i,\pm} < \bar{R}_{i,\pm} \) which implies

\[
\partial_{i,\pm,M_{i,\pm}}(\Sigma(u)) := \{ p \in \Sigma(u) \cap U_{i,\pm} \mid |\bar{\eta}_{i,\pm}(p)| < M_{i,\pm} \subset \Sigma \cap U_{i,\pm}
\]

for all \( \Sigma(u) \in \mathcal{B}_{\Sigma_0} \). This allows us to define the map \( \gamma : \mathcal{B}_{\Sigma_0} \to Discs_{\text{Ram}}^{\mathcal{B}_{\Sigma_0}} \) and \( i : G \to W_{\text{Ram}} \). As we are about to see, this is also sufficient for us to define the section \( \theta \in \Gamma(B_{\Sigma_0}, G) \) and to perform any relevant parallel transports in \( G \).

### 3.2.4 The embedding \( \mathcal{B}_{\Sigma_0} \hookrightarrow Discs_{\Sigma_0}^{M_{i,\pm}} \hookrightarrow W_{\epsilon_{i,\pm}}^{\epsilon_{i,\pm}} \)

Let \( \theta_{t_{i,\pm}}(\Sigma) = -\bar{z}_{i,\pm} d\bar{w}_{i,\pm} = -\sum_{k=0}^{\infty} b_{t_{i,\pm},k}(\Sigma) \bar{\eta}_{i,\pm}^k (\bar{\eta}_{i,\pm}^2 + F_{i,\pm}(P(z_i(u);u))) \in T_0 L_{\text{Airy}}^{M_{i,\pm}} \subset W_{\epsilon_{i,\pm},t_{i,\pm}}^{\epsilon_{i,\pm}} \).

The embedding \( \Phi_{t_{i,\pm}}(\Sigma_0) = Discs_{\Sigma_0}^{M_{i,\pm}} \hookrightarrow W_{\epsilon_{i,\pm}}^{\epsilon_{i,\pm}} \) is given by

\[
\Phi_{t_{i,\pm}}(\Sigma_0)(t_{i,\pm}(\Sigma)) = -\partial_{t_{i,\pm}}(\Sigma)+ \exp \left( -F_{i,\pm}(P(z_i(u);u)) \mathcal{L}_{\frac{\partial}{\partial \bar{w}_{i,\pm}}} \theta_{t_{i,\pm}}(\Sigma) \right) \theta_{t_{i,\pm}}(\Sigma)
\]

\[
\begin{align*}
&= \bar{\eta}_{i,\pm} d\bar{\eta}_{i,\pm}^2 - \exp \left( -F_{i,\pm}(P(z_i(u);u)) \mathcal{L}_{\frac{\partial}{\partial \bar{w}_{i,\pm}}} \theta_{t_{i,\pm}}(\Sigma) \right) \\
&= \sum_{k=0}^{\infty} b_{t_{i,\pm},k}(\Sigma) \bar{\eta}_{i,\pm}^k \frac{d\bar{\eta}_{i,\pm}}{\partial \bar{\eta}_{i,\pm}} \in L_{\text{Airy}}^{M_{i,\pm}} \subset W_{\epsilon_{i,\pm}}^{\epsilon_{i,\pm}} \subset W_{\epsilon_{i,\pm},t_{i,\pm}}^{\epsilon_{i,\pm}}.
\end{align*}
\]

We note that \( \exp \left( -F_{i,\pm}(P(z_i(u);u)) \mathcal{L}_{\frac{\partial}{\partial \bar{w}_{i,\pm}}} \theta_{t_{i,\pm}}(\Sigma) \right) \theta_{t_{i,\pm}}(\Sigma) \in W_{\epsilon_{i,\pm}}^{\epsilon_{i,\pm}} \) according to Lemma 2.4.9 because \( |F_{i,\pm}(P(z_i(u);u))| < \epsilon_{i,\pm} \) for all \( \Sigma(u) \in \mathcal{B}_{\Sigma_0} \).
3.2.5 The embedding $\mathcal{B}_{\Sigma_0} \hookrightarrow G_{\Sigma_0}$

To obtain the embedding $\Phi_{\Sigma_0} : \mathcal{B}_{\Sigma_0} \hookrightarrow G_{\Sigma_0}$ we will first define $\theta \in \Gamma(\mathcal{B}_{\Sigma_0}, G)$ by

$$\theta_{\Sigma(u)} := dS_{SW}(\Sigma(u)) - s_{\Sigma(u),\Sigma_0}^* dS_{SW}(\Sigma_0) \in G_{\Sigma(u)}, \quad \forall [\Sigma(u)] \in \mathcal{B}_{\Sigma_0}.$$

Let us elaborate on the definition of $s_{\Sigma(u),\Sigma_0}^* dS_{SW}(\Sigma_0)$ in this context. Let $p \in \Sigma(u) \setminus \{ r_{\alpha \in \mathcal{R}_a(G)} \}$, then $dw_{i \pm}(p) \neq 0$. Hence, there exists an open neighbourhood $V_p \subset \Sigma(u)$ of $p$ such that $w_{i \pm}$ is a local coordinate of $V_p$. Then we define $s_{\Sigma(u),\Sigma_0}^* dS_{SW}(\Sigma_0)|_{V_p \cap \Sigma} := z_p \left( w + \frac{1}{w}; u \right) dw$. Where $z_p \left( w + \frac{1}{w}; u \right) = z_p(w_{i \pm}; u_0)$ is the root of $P(z; u_0) - w_{i \pm} = 0$ such that $(w, z_p \left( w + \frac{1}{w}; u \right)) \in \Sigma_0$ varies continuously to $(w, z_p \left( w + \frac{1}{w}; u \right)) \in V_p \subset \Sigma(u)$ as we move continuously from $u_0$ to $u$, where $z_p(w_{i \pm}; u)$ is a root of $P(z; u) - w_{i \pm} = 0$. It follows that on $V_p$ we have $\theta_{\Sigma(u)}$ given by

$$\theta_{\Sigma(u)}|_{V_p} = z_p \left( w + \frac{1}{w}; u \right) dw - z_p \left( w + \frac{1}{w}; u_0 \right) dw.$$

Of course, $\theta_{\Sigma(u)}$ is not a single-valued differential form on $\Sigma(u)$ because if $V_p$ contains a ramification point $r_{i \pm}(\Sigma(u)) \in \Sigma(u)$ then

$$z_p \left( w + \frac{1}{w}; u \right) = z_i(u_0) + \left( \frac{2}{P'(z_i(u_0)); u_0} \right)^{\frac{1}{2}} \sqrt{w + \frac{1}{w} - P(z_i(u_0); u_0) + ...}$$

$$= z_i(u_0) + \left( \frac{2}{P'(z_i(u_0)); u_0} \right)^{\frac{1}{2}} \sqrt{\eta_0^2 + P(z_i(u)); u_0} - P(z_i(u); u_0) + ...$$

Where $n_{i \pm}$ is the standard local coordinates on $\Sigma \cap U_{i \pm}$ corresponding to the local coordinates $(w_{i \pm}, z_{i \pm})$ and $w_{i \pm} = \eta_0^2 + P(z_i(u); u)$ (see (3.10)). The term $\sqrt{\eta_0^2 + P(z_i(u)); u_0}$ acquires a negative sign whenever $n_{i \pm}$ moves around the point $\pm \sqrt{P(z_i(u); u) - P(z_i(u); u_0)}$.

What happening is, for each fixed $w$ the value of $z$ can be any one of $g + 1$ distinct roots of $P(z; u_0) - w - \frac{1}{w} = 0$ except when $w + \frac{1}{w}$ is a critical value of $P(z; u_0)$ two of the roots will coincide and we are left with only $g$ distinct roots. As $w + \frac{1}{w}$ moves around the critical value $z(w; u_0)$ will switch between the two roots of $P(z; u_0) - w - \frac{1}{w} = 0$ that is true when $w + \frac{1}{w}$ is the critical value. However, $\theta_{\Sigma(u)}$ becomes single-valued once we remove the discs $D_{i \pm, \epsilon_{i \pm}}(\Sigma(u))$ from the curve $\Sigma(u)$ i.e. $\theta_{\Sigma(u)}$ is a single-valued differential form on $\Sigma(u) \setminus \cup_{i=1}^g (\bar{D}_{i \pm, \epsilon_{i \pm}})$ for some $\epsilon_{i \pm} < \epsilon_{i \pm}$.

Note that although $dS_{SW}(\Sigma_0) \notin G_{\Sigma_0}$, we indeed have $\theta_{\Sigma(u)} \in G_{\Sigma(u)}$. Before the blow-ups, $dS_{SW}(\Sigma_0)$ and $dS_{SW}(\Sigma(u))$ both have poles of order 2 at $\infty_+:=(w = 0, z = \infty), \infty_- := (w = \infty, z = 0)$, on $\Sigma_0$ and $\Sigma(u)$ respectively, without residues and they are holomorphic elsewhere. The poles at $\infty_{i \pm}$ from $dS_{SW}(\Sigma_0)$ and $dS_{SW}(\Sigma(u))$ will cancel out in the expression of $\theta_{\Sigma(u)}$. The same remains true after blow-ups. So $\theta_{\Sigma(u)}$ is holomorphic on $\Sigma(u) \setminus \cup_{i=1}^g (\bar{D}_{i \pm, \epsilon_{i \pm}})$ for some $\epsilon_{i \pm} < \epsilon_{i \pm}$. Lastly, we also have

$$\int_{\partial D_{i \pm, \epsilon_{i \pm}}} \theta_{\Sigma(u)} = \int_{\partial D_{i \pm, \epsilon_{i \pm}}} dS_{SW}(\Sigma(u)) - \int_{\partial D_{i \pm, \epsilon_{i \pm}}} s_{\Sigma(u),\Sigma_0}^* dS_{SW}(\Sigma_0) = 0$$

using the same argument presented in the proof of Lemma 2.5.31 and the fact that $dS_{SW}$ has no poles around the ramification points $\{ r_{\alpha \in \mathcal{R}_a} \}$. Therefore, we conclude that $\theta_{\Sigma} \in G_{\Sigma}$. Now we can define $\Phi_{\Sigma_0}$ by

$$\Phi_{\Sigma_0}(\Sigma(u)) := \theta_{\Sigma_0} - s_{\Sigma_0,\Sigma_0}^* \theta_{\Sigma(u)} = dS_{SW}(\Sigma_0) - s_{\Sigma_0,\Sigma_0}^* dS_{SW}(\Sigma_0) \in G_{\Sigma_0}. \quad \text{(3.20)}$$

Example 3.2.1 In the Elliptic case $g = 1$, $\Sigma : w + \frac{1}{w} = z^2 + u$, the equation (3.20) simplifies to

$$\Phi_{\Sigma_0}(\Sigma(u)) = \sqrt{w + \frac{1}{w} - u_0} dw - \sqrt{w + \frac{1}{w} - u} dw.$$

It is clear by choosing $A$ and $B$-cycles on $\Sigma_0$ avoiding the discs $\bar{D}_{i \pm, \epsilon_{i \pm}}(\Sigma_0)$ we have

$$\int_{A_i} \Phi_{\Sigma_0}(\Sigma(u)) = a_i^0 - a_i, \quad \int_{B_i} \Phi_{\Sigma_0}(\Sigma(u)) = 0_i^0 - b_i = \frac{\partial \Phi_{\Sigma_0}^{SW}}{\partial a_i^0}(a_0) - \frac{\partial \Phi_{\Sigma_0}^{SW}}{\partial a_i^0}(a), \quad i = 1, ..., g$$

where

$$a_i = a_i(\Sigma(u)) := \int_{A_i} dS_{SW}(\Sigma(u)), \quad b_i = b_i(\Sigma(u)) := \int_{B_i} dS_{SW}(\Sigma(u)) = \frac{\partial \Phi_{\Sigma_0}^{SW}}{\partial a_i^0}(a),$$
Let us now express $\Phi_{SW}$.

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Let us compute contractible set and the principal part of $\Phi_{SW}$. We rewrite (3.20) on $A_{i\pm, \xi \pm, M \pm} \cap V_p$ in the local coordinates $(w_{i \pm}, \bar{z}_{i \pm})$ as

$$\Phi_{SW}(\Sigma(u))|_{A_{i\pm, \xi \pm, M \pm} \cap V_p} = \sum_{\xi} \left( \sqrt{F^{-1}_{i \pm}(\bar{w}_{i \pm}) - P(z_{i}(u); u)}; u \right) \frac{d\bar{w}_{i \pm}^{2}}{2} = \frac{z}{z_{odd}} \left( \sqrt{F^{-1}_{i \pm}(\bar{w}_{i \pm}) - P(z_{i}(u); u)}; u \right) \frac{d\bar{w}_{i \pm}^{2}}{2} - \frac{z}{z_{even}} \left( \sqrt{F^{-1}_{i \pm}(\bar{w}_{i \pm}) - P(z_{i}(u); u)}; u \right) \frac{d\bar{w}_{i \pm}^{2}}{2}.$$

On $A_{i\pm, \xi \pm, M \pm} \subset \Sigma_0$ we have $\bar{w}_{i \pm} = \bar{\eta}_{i \pm}^{2} + F_{i \pm} (P(z_{i}(u_{0}); u_{0})) = \bar{\eta}_{i \pm}^{2}$ and using (3.15) it follows that

$$\bar{\eta}_{i \pm} = \Phi_{SW}(\Sigma(u))|_{A_{i\pm, \xi \pm, M \pm}}.$$

Evidently, we have an agreement: $i \circ \Phi_{SW}(\Sigma(u)) = \Phi_{SW}(\Sigma(u)) \circ \gamma(\Sigma)$. In particular, each $\bar{\eta}_{i \pm} = \Phi_{SW}(\Sigma(u)) = \sum_{k \neq 0} J_{k}(u)\eta_{i \pm}^{k} \frac{d\eta_{i \pm}^{k}}{\eta_{i \pm}^{k}}$ satisfies the residue constrains and therefore, $i \circ \Phi_{SW}(\Sigma(u)) = \sum_{i=1}^{g} \sum_{k \neq 0} J_{k}(u)[i \pm] \otimes \bar{\eta}_{i \pm}^{k} \frac{d\eta_{i \pm}^{k}}{\eta_{i \pm}^{k}} \in \mathcal{P}_{\Sigma_{0}}^{Ram} \in W_{Ram}$.  

3.3 Seiberg-Witten Prepotential and Topological Recursion

Let us now express $\Phi_{SW}(\Sigma(u))$ in terms of the normalized holomorphic differential $\{\omega_{i=1, \ldots, g}\}$ and meromorphic differentials $\{e^{k \pm}\}$ (see Definition 2.5.10) on $\Sigma_{0}$. From Corollary 2.5.16 the fact that $\Phi_{SW}(\Sigma(u)) \in G_{\Sigma_{0}}$ and the principal part of $i_{\pm} \circ \Phi_{SW}(\Sigma(u))$ is the principal part of $i_{\pm} \circ \Phi_{SW}(\Sigma(u)) = \Phi_{SW}(\Sigma_{0})(t_{i \pm}(\Sigma))$ which is $\sum_{k>0} J_{k}(u)\eta_{i \pm}^{k} \frac{d\eta_{i \pm}^{k}}{\eta_{i \pm}^{k}}$, we have

$$\Phi_{SW}(\Sigma(u)) = \sum_{i=1}^{g} \sum_{k>0} \left( J_{k}^{+}(u)e^{k,i} + J_{k}^{-}(u)e^{k,j} \right) + \sum_{i=1}^{g} \left( a_{i} - a_{i} \right) \omega_{i}. \quad (3.21)$$

Another way to look at this is that the principal part of $\sum_{i=1}^{g} \sum_{k>0} \left( J_{k}^{+}(u)e^{k,i} + J_{k}^{-}(u)e^{k,j} \right)$ exactly matches that of $\Phi_{SW}(\Sigma(u))$. Therefore, $\Phi_{SW}(\Sigma(u)) - \sum_{i=1}^{g} \sum_{k>0} \left( J_{k}^{+}(u)e^{k,i} + J_{k}^{-}(u)e^{k,j} \right)$ can be analytically extended to a meromorphic differential form defined on the entire curve $\Sigma_{0}$, and it is, in fact, a holomorphic on $\Sigma_{0}$ because neither term has singularity anywhere except at ramification points $\tau_{\alpha}, \alpha \in Ram$. Subtracting $\sum_{i=1}^{g} (a_{i} - a_{i}) \omega_{i}$, we get a global holomorphic differential form on $\Sigma_{0}$ with vanishing $A$-periods, hence must be identically zero and (3.21) follows.

Let us extend the set $\{\omega_{1}, \ldots, \omega_{g}\}$ into a new canonical basis of $W_{Ram}$. First, let us compute the $\Omega_{Airy}$ symplectic pairings between $\{e^{k \pm}\}$ and $\{\omega\}$. Suppose that

$$i(\omega_{i}) = \sum_{i=1}^{g} \sum_{k=1}^{\infty} \left( c^{i,j}_{k}[i] \otimes k^{i}_{+} \frac{d\eta_{i+}}{\eta_{i+}} + c^{i,j}_{k}[i] \otimes k^{i}_{-} \frac{d\eta_{i-}}{\eta_{i-}} \right)$$

then

$$\oint_{p \in B_{i}} e^{k,i}(p) = \frac{1}{2\pi i k} \oint_{p \in B_{i}} B(p, q(\bar{\eta}_{i \pm})) \frac{1}{\eta_{i \pm}} \frac{1}{\bar{\eta}_{i \pm}} \oint_{p \in B_{i}} B(p, q(\bar{\eta}_{i \pm})) \int_{\eta_{i \pm}=0}^{1} \frac{1}{\eta_{i \pm}} \frac{1}{\bar{\eta}_{i \pm}} \oint_{p \in B_{i}} B(p, q(\bar{\eta}_{i \pm}))$$

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\[ \frac{1}{k} \oint_{\eta \pm = 0} \frac{1}{\eta^k_{\pm}} \omega_j(q(\eta_{\pm})) = 2\pi i c_j^{k,+}. \]

Then it follows that the symplectic pairings are
\[ \Omega_{\text{Airy}}(e^{k,+}, \omega_j) = \frac{1}{2\pi i} \left( \oint_{A_1} \omega_j \oint_{B_1} e^{k,+} - \oint_{B_1} \omega_j \oint_{A_1} e^{k,+} \right) = \frac{1}{2\pi i} \oint_{B_1} e^{c,k,+} = c_j^{k,+}. \]

This shows that \( \{ \omega_i, e^{k,+} | i = 1, \ldots, g, k \geq 2 \} \) cannot be extended to a canonical basis. Let us examine some properties of the coefficients \( c_j^{k,+} \).

**Lemma 3.3.1** \( c_j^{k,+} = -c_j^{k,-}. \)

**Proof:** We note that each normalized holomorphic differential form \( \omega_i \) can be written as a linear combination of \( \{ \frac{i \cdot \eta^j_{\pm}}{w} | i = 1, \ldots, g \} \). Since we can map the neighbourhood \( \Sigma_0 \cap U_{i+} \) of each ramification point \( r_{i+} \) to the corresponding neighbourhood \( \Sigma_0 \cap U_{i-} \) of \( r_{i-} \) via the involution \( p = (z, w) \rightarrow \hat{p} = (z, \frac{1}{w}) \), it follows that \( \omega_k(p) = -\omega_k(\hat{p}) \). Let us examine the involution in terms of the standard local coordinates \( u_{\pm} \) defined in (3.19). Suppose that \( p \in \Sigma_0 \cap U_{i+} \). First, we note that we have \( \eta_{i+}(p) = \eta_{i-}(\hat{p}) \) because \( \eta^2_{\pm} = P(z; u) - P(z; u) \) and \( z(p) = z(\hat{p}) \). Because we have chosen \( F_{i+} \) and \( F_{i-} \) to be the same (see (3.15)), therefore the relationship between \( \eta_{\pm} \) and \( \eta_{\pm} \) as given in (3.19) implies that \( \eta_{i+}(p) = \eta_{i-}(\hat{p}) \). Writing \( \omega_k(p) = -\omega_k(\hat{p}) \) in the standard local coordinates we have
\[ \sum_{k=0}^{\infty} c_j^{k,+} k^{n-k}(p) \frac{d\eta_i(p)}{\eta_i(p)} = \frac{d\eta_i(p)}{\eta_i(p)} \frac{d\eta_i(p)}{\eta_i(p)} = -\sum_{k=0}^{\infty} c_j^{k,-} k^{n-k}(p) \frac{d\eta_i(p)}{\eta_i(p)} \frac{d\eta_i(p)}{\eta_i(p)}, \]
from which we conclude that \( c_j^{k,+} = -c_j^{k,-}. \)

Let \( (c_j^{i}) \) be a \( g \times g \) matrix where \( c_j^{i} = c_j^{1,+} = -c_j^{1,-}. \)

**Lemma 3.3.2** The matrix \( (c_j^{i}) \) is invertible.

**Proof:** Let \( (a^i) \in \mathbb{C}^g \) be a vector such that \( \sum_{j=1}^{g} c_j^{i} a^j = 0. \) Then \( \omega := \sum_{j=1}^{g} a^j \omega_j \) is a holomorphic differential form on \( \Sigma_0 \) such that
\[ \omega(r_{i \pm}) = \frac{1}{2\pi i} \oint_{\eta \pm = 0} \omega(q(\eta_{\pm})) = \sum_{j=1}^{g} c_j^{i} a^j = \pm \sum_{j=1}^{g} c_j^{i} a^j = 0. \]
for all \( i \in \text{Ram} \). So \( \omega \) vanishes at every ramification points and therefore has at least 2g zeros and has no poles. But \( \text{deg}K_{\Sigma_0} = 2g - 2 < 2g \) which is a contradiction, unless \( (a^i) = 0. \) In other words, \( (c_j^{i}) \) is invertible.

Let \( (b_j^{i}) \) be the inverse of \( (c_j^{i}) \), i.e. \( \sum_{k=1}^{g} b_k^{i} c_j^{k} = \delta_j^{i}. \) Now, let us choose a new canonical basis for \( W_{\text{Airy}}^{\text{Ram}} \) to be
\[ \{ i^+, i^+, r^{k,+}, \omega_i, \omega_k, \omega_{k,\pm} | i = 1, \ldots, g, k \geq 2 \} \]
(3.22)
where
\[ r^{i} := \frac{1}{2} \sum_{j=1}^{g} b_k^{j} (e^{1,j+} - e^{1,j-}) = \frac{1}{2} \sum_{j=1}^{g} b_k^{j} (e^{1,j+} + e^{1,j-}) = \frac{1}{2} \sum_{j=1}^{g} c_j^{k,+} b_j^{i} e^{1,i}; \]
\[ \omega_{i} := \sum_{j=1}^{g} \sum_{k=1}^{\infty} \left( c_j^{k,+} [j+] \otimes k^n \frac{d\eta_{i}^{j+}}{\eta_{i}^{j+}} - c_j^{k,-} [j-] \otimes k^n \frac{d\eta_{i}^{j-}}{\eta_{i}^{j-}} \right), \]
\[ \omega^{k,+} := [i^+] \otimes k^n \frac{d\eta_{k,+}}{\eta_{k,+}}. \]

Note that this is the type of gauge transformation we studied in Section 2.4.2 and Section 2.5.4.

**Remark 3.3.3** Observe that \( r^{i}, r^{i}, r^{k,+} \) and \( \omega_i \) are all global meromorphic differential forms on \( \Sigma_0 \) belonging to \( G_{\Sigma_0} \) while \( \omega_i, \omega_{k,\pm} \in W_{\text{Airy}}^{\text{Ram}} \) are only locally defined near each ramification points \( r_{i \pm}. \)
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To confirm that we have defined a canonical basis we can check that for \( i, j = 1, \ldots, g, \alpha, \beta \in \text{Ram} \) and \( k \geq 2 \) we have

\[
\Omega_{\text{Airy}}(\tau^i, \omega_j) = \delta^i_j, \quad \Omega_{\text{Airy}}(\bar{\tau}^i, \bar{\omega}_j) = \delta^i_j, \quad \Omega_{\text{Airy}}(\tau^{k,\alpha}, \omega_{l,\beta}) = \delta^k\delta^\alpha_l \delta^\beta_k
\]

and all other pairings vanish. In particular,

\[
\oint_{A_i} \omega_j = \delta^i_j, \quad \oint_{B_j} \omega_j = \tau_{ij}(a_0), \quad \oint_{A_i} \tau^j = 0, \quad \oint_{B_j} \tau^j = 2\pi i \delta^i_j \tag{3.23}
\]

and all \( A, B \)-periods of \( \bar{\tau}^i, e^{k,\pm} \) are zero. Substitute \( e^{k,\pm} = \sum_{j=1}^g c^i_j (\bar{\tau}^j \pm \tau^j) \), \( e^{k,\pm} = \tau^{k,\pm} + \sum_{j=1}^g e^{k,\pm}_j (\bar{\tau}^j \pm \tau^j) \) into (3.21) and recollect terms, we can rewrite (3.21) as

\[
\Phi_{\Sigma_0}(\Sigma(u)) = \sum_{i=1}^g \left( \alpha^i \omega_i + \bar{\tau}^i \bar{\omega}_i + \sum_{k=2}^\infty (\bar{\tau}^{k,\pm} \omega_{k,i} + \tau^{k,\pm} \bar{\omega}_{k,i}) \right) + \sum_{j=1}^g \left( \beta_j \tau^j + \bar{\tau}^j \bar{\omega}_j + \sum_{k=2}^\infty (\bar{\tau}_{k,j} \tau^{k,\pm} + \tau_{k,j} \bar{\tau}^{k,\pm}) \right) \tag{3.24}
\]

where

\[
\alpha^i = a_0^i - a^i, \quad \bar{\tau}^i = 0, \quad \bar{\tau}^{k,\pm} = 0, \quad \beta_j = \sum_{k=1}^\infty \left( c^j_{k,j} (\tau^k_j + (u) - c^{j,-}_{k,j} (\tau^k_j (u)) \right),
\]

\[
\bar{\omega}_j = \sum_{k=1}^\infty \sum_{j=1}^\infty \left( c^j_{k,j} (\tau^k_j + (u) + c^{j,-}_{k,j} (\tau^k_j (u)) \right), \quad \bar{\omega}_{k,i} = J^{k,i+}_j(u).
\]

There is no technical difficulties involved in recollection of terms because \( e^{k,\pm} \) are written as a finite sum of \( \tau^i, \bar{\tau}^i, \tau^{k,\pm} \) and infinite sums commute with finite sums.

Let \( (V_{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}) \) be the gauge transformed quantum Airy structure of \( (V_{\text{Ram}}, A_{\text{Airy}}, B_{\text{Airy}}, C_{\text{Airy}}, \epsilon_{\text{Airy}}) \) corresponding to the basis (3.22) of \( W_{\text{Ram}}^{\text{Airy}} \). The ATR output is given by

\[
S = \sum_{n=0}^\infty h^{n-1} S_g \text{ where } S_g = \sum_{n=1}^\infty S_{g,n},
\]

\[
S_{g,n} = S_{g,n} \left( \{\alpha^i\}, \{\bar{\tau}^i\}, \{\bar{x}^{k,\pm}\} \right)
\]

\[
= \sum \frac{1}{n_1! n_2! n_3!} \sum_{i_1, \ldots, i_n = 1, \ldots, g} \sum_{j_1, \ldots, j_n = 1, \ldots, g} \sum_{k_1, \ldots, k_n = 1, \ldots, g} \sum_{\alpha^1, \ldots, \alpha^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n} \frac{\partial S_{0,\alpha^1, \ldots, \alpha^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n}}{\partial \alpha^1 \partial \bar{\alpha}^1 \cdots \partial \alpha^n \partial \bar{\alpha}^n \cdots \partial \bar{\alpha}^n} \bigg|_{\alpha^1 = \alpha^i, \alpha^n, \bar{\alpha}^1 = \bar{\alpha}^i, \bar{\alpha}^n, \bar{\alpha}^1 = \bar{\alpha}^i, \bar{\alpha}^n}
\]

where

\[
S_{g,n,\alpha^1, \ldots, \alpha^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n} = \sum_{i_1, \ldots, i_n, j_1, \ldots, j_n, k_1, \ldots, k_n} \sum_{\alpha^1, \alpha^n, \bar{\alpha}^1, \bar{\alpha}^n} \frac{\partial S_{0,\alpha^1, \ldots, \alpha^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n, \bar{\alpha}^1, \ldots, \bar{\alpha}^n}}{\partial \alpha^1 \partial \bar{\alpha}^1 \cdots \partial \alpha^n \partial \bar{\alpha}^n \cdots \partial \bar{\alpha}^n} \bigg|_{\alpha^1 = \alpha^i, \alpha^n, \bar{\alpha}^1 = \bar{\alpha}^i, \bar{\alpha}^n, \bar{\alpha}^1 = \bar{\alpha}^i, \bar{\alpha}^n}
\]

Since \( \Phi_{\Sigma_0}(\Sigma(u)) \in L^{\text{Ram}}_{\text{Airy}}, \) it follows that we can re-write (3.24) as

\[
\Phi_{\Sigma_0}(\Sigma(u)) = \sum_{i=1}^g (a^i_0 - a^i) \omega_i + \sum_{i=1}^g \left( \frac{\partial S_{0}}{\partial a^i} \big|_{a^i = a^i_0 - a^i} \tau^i \right) + \frac{\partial S_{0}}{\partial \bar{\tau}^i} \bigg|_{\bar{\tau}^i = 0} + \frac{\partial S_{0}}{\partial \bar{\tau}^i} \bigg|_{\bar{\tau}^i = 0} \tag{3.25}
\]

Let \( S_0 = S_0(\alpha^1, \ldots, \alpha^n) := S_0(\{\alpha^i\}, \{\bar{\tau}^i = 0\}, \{\bar{x}^{k,\pm} = 0\}) \). Compute the \( B \)-periods of \( \Phi_{\Sigma_0}(\Sigma(u)) \) using (3.25), (3.23) and the fact that \( \frac{\partial}{\partial \bar{\tau}^i} = -\frac{\partial}{\partial \tau^i} \). We get

\[
\frac{\partial \Phi_{\Sigma_0}^{SW}}{\partial a^i} (a^1_0, \ldots, a^n_0) = \frac{\partial \Phi_{\Sigma_0}^{SW}}{\partial a^i} (a^1, \ldots, a^n) \int_{B_i} \Phi_{\Sigma_0}(\Sigma(u)) = \sum_{j=1}^g (a^j_0 - a^j) \tau_{ij}(a_0) - 2\pi i \frac{\partial S_0(a^1 - a^1_0, \ldots, a^n_0 - a^n)}{\partial a^i}.
\]
Integrating both sides we obtain

\[
\delta^{SW}_{\Sigma_0}(a^1, \ldots, a^g) = \delta^{SW}_{\Sigma_0}(a_0^1, \ldots, a_0^g) + \sum_{i=1}^{g} (a^i - a_0^i) \frac{\partial \delta^{SW}_{\Sigma_0}}{\partial a^i}(a_0^1, \ldots, a_0^g) \\
+ \frac{1}{2} \sum_{i,j=1}^{g} (a^i - a_0^i)(a^j - a_0^j) \frac{\partial^2 \delta^{SW}_{\Sigma_0}}{\partial a^i \partial a^j}(a_0^1, \ldots, a_0^g) + 2\pi i S_0(a_0^1 - a^1, \ldots, a_0^g - a^g).
\]  

Let us consider a topological recursion with spectral curve \((\Sigma_0), \log w, z, B)\) where \(\Sigma_0\) is the Seiberg-Witten curve given by \(w + \frac{1}{w} = P(z; u_0)\) and \(B = B(p, q)\) is the normalized Bergman kernel on \(\Sigma_0 \times \Sigma_0\). The initial condition of the recursion shall be given by

\[
\omega_{0,1}(p) = z(p) \frac{dw(p)}{w(p)} = dS_{SW}(p), \quad \omega_{0,2}(p, q) = B(p, q).
\]

It is easy to check using \((3.18)\) that in the standard local coordinate \(\eta_{\pm}\) in the neighbourhood \(\Sigma_0 \cap U_{\pm}\) of each ramification point \(r_{\pm}(\Sigma_0)\) we have

\[
\omega_{0,1}(\eta_{\pm}) - \omega_{0,1}(-\eta_{\pm}) = 4\eta_{\pm}^2 d\eta_{\pm}.
\]

From Proposition 2.6.2 the output meromorphic multi-differential forms are given by

\[
\omega^{SW}_{g,n}(p_1, \ldots, p_n) = \sum_{\sigma \in S_n} \sum_{n_1, n_2, n_3 \geq 0} \frac{1}{n_1! n_2! n_3!} \sum_{i_1, \ldots, i_n = 1}^{g} S_{g,n,\alpha^i_1 \ldots \alpha^i_n}(p_{\sigma(1)1}, \ldots, p_{\sigma(n)1}) \cdot \tau_{\alpha^1}(p_{\sigma(1)1}) \cdot \ldots \cdot \tau_{\alpha^n}(p_{\sigma(n)1}) \cdot \frac{\partial^{\alpha^1}(p_{\sigma(1)1}) \cdot \ldots \cdot \partial^{\alpha^n}(p_{\sigma(n)1})}{n_1! n_2! n_3!}
\]

where the superscript \(\text{SW}\) is added to signify that \(\omega^{SW}_{g,n}\) are produced from topological recursion using Seiberg-Witten curve as initial data. Then we have

\[
\oint_{p_1 \in B_{i_1}} \ldots \oint_{p_n \in B_{i_n}} \omega^{SW}_{g,n}(p_1, \ldots, p_n) = (2\pi i)^n S_{g,n,\alpha^i_1 \ldots \alpha^i_n}.
\]

By definition we have

\[
2\pi i S_0(a_0^1 - a^1, \ldots, a_0^g - a^g) = \sum_{n=1}^{\infty} \frac{1}{n!} \sum_{i_1, \ldots, i_n = 1}^{g} S_{0,n,\alpha^i_1 \ldots \alpha^i_n}(a_0^i - a^i)(a_0^i - a^i) = \sum_{n=1}^{\infty} \frac{(-1)^n}{n!} \sum_{i_1, \ldots, i_n = 1}^{g} \oint_{p_1 \in B_{i_1}} \ldots \oint_{p_n \in B_{i_n}} \omega^{SW}_{0,n}(p_1, \ldots, p_n) \cdot (a^i - a^i)(a^i - a^i).
\]

Therefore, we arrive at the relation between the Seiberg-Witten prepotential \(\delta^{SW}_{\Sigma_0}\) and meromorphic multi-differential forms \(\omega_{0,n}\) produced from topological recursion:

\[
\delta^{SW}_{\Sigma_0}(a^1, \ldots, a^g) = \delta^{SW}_{\Sigma_0}(a_0^1, \ldots, a_0^g) + \sum_{i=1}^{g} (a^i - a_0^i) \frac{\partial \delta^{SW}_{\Sigma_0}}{\partial a^i}(a_0^1, \ldots, a_0^g) + \frac{1}{2} \sum_{i,j=1}^{g} (a^i - a_0^i)(a^j - a_0^j) \frac{\partial^2 \delta^{SW}_{\Sigma_0}}{\partial a^i \partial a^j}(a_0^1, \ldots, a_0^g) \\
- \sum_{n=1}^{\infty} \frac{1}{2\pi} \sum_{i_1, \ldots, i_n = 1}^{g} \oint_{p_1 \in B_{i_1}} \ldots \oint_{p_n \in B_{i_n}} \omega^{SW}_{0,n}(p_1, \ldots, p_n) \cdot (a^i - a^i)(a^i - a^i),
\]  

on the open neighbourhood \(B_{\Sigma_0} \subseteq B\) of \([\Sigma_0] \in \mathcal{B}\). This agrees with the result of Theorem 2.7.3 after identifying \(a^i := -a^i\) and \(\delta_B(a^1, \ldots, a^g) = \delta^{SW}_{\Sigma_0}(a^1, \ldots, a^g)\).
Chapter 4

Seiberg-Witten Theory and Frobenius Manifolds

In this chapter, we investigate how Seiberg-Witten theory arises from a certain construction of Frobenius manifolds as proposed by Dubrovin [10]. We start in Section 4.1 with a brief review of the definition of Frobenius manifold and some basic facts which can found in [11, 9]. Some examples of Frobenius manifolds will be provided in Section 4.2. In Section 4.3, we review the tensor product construction of Frobenius manifolds [11, 22]. Then we will discuss in detail in Section 4.4 how a system of $2g$-linearly independent odd periods on the coordinate cross of $M_A \otimes QH^*(\mathbb{P}^1)$ is given by the $A$ and $B$ periods of the Seiberg-Witten differential $dS_{SW}$ on the Seiberg-Witten family of curves as proposed in [10]. Finally, in Section 4.5 we will show that in general, a $\nu$-period of an arbitrary tensor product Frobenius manifold $M = M' \otimes M''$ can be obtained as a period integral on some Riemann surface. This allows us to work backward starting from Seiberg-Witten theory then find that of odd periods of $M = M' \otimes M''$ are given by the periods of $dS_{SW}$ then $M' = M_A$ and $M'' = QH^*(\mathbb{P}^1)$.

4.1 Frobenius Manifolds

Definition 4.1.1 ([10, 11, 9]) A Frobenius algebra is a commutative associative algebra $A$ over a field $k$ ($= \mathbb{R}$ or $\mathbb{C}$) together with a $k$-bilinear symmetric nondegenerate form $\langle . , . \rangle$ satisfying the invariant condition:

$$\langle x \cdot y, z \rangle = \langle x, y \cdot z \rangle, \quad \forall x, y, z \in A$$

Definition 4.1.2 ([10, 11, 9]) A Frobenius structure on a complex manifold $M$ of (complex) dimension $n$ with holomorphic metric tensor $\langle . , . \rangle$ is a Frobenius algebra defined on the holomorphic tangent space $T_t M = (A_t, \langle . , . \rangle_t)$ depending holomorphically on $t \in M$. A Frobenius manifold is a complex manifold $M$ with Frobenius structure satisfying the following axioms:

A1 The metric $\langle . , . \rangle$ is a flat metric (in other words, the Riemann curvature tensor $R^\alpha_{\beta\gamma}$ vanishes).

A2 Let $c(x, y, z) := \langle x \cdot y, z \rangle_t$, $x, y, z \in T_t M$. Then the 4-tensor $(\nabla_w c)(x, y, z)$ must be symmetric in $x, y, z, w \in T_t M$.

A3 There exists the unity vector field $e \in \Gamma(M, TM)$, the unit for the algebra $(T_t M, \langle . , . \rangle_t)$ for all $t \in M$, which is covariantly constant $\nabla e = 0$ and there exists an Euler vector field $E \in \Gamma(M, TM)$ satisfying $\nabla \nabla E = 0$ and

$$[E, x \cdot y] - [E, x] \cdot y - x \cdot [E, y] = x \cdot y$$

$$E \langle x, y \rangle - \langle [E, x], y \rangle - \langle x, [E, y] \rangle = (2 - d) \langle x, y \rangle.$$

The integer $d$ is called the charge of the Frobenius manifold.

Where we have denoted by $\nabla$, the Levi-Civita connection for the metric.

The fact that $\langle . , . \rangle$ is flat means we can locally find flat coordinates $\{t^\alpha\}$, which are holomorphic coordinates such that $\eta_{\alpha\beta} := \langle \frac{\partial}{\partial t^\alpha}, \frac{\partial}{\partial t^\beta} \rangle$ is constant. We let $\eta^{\alpha\beta}$ be the inverse of $\eta_{\alpha\beta}$ and as a slight abuse of notation we
will use $\langle ., . \rangle$ as a metric on the cotangent space such that $\langle dt^\alpha, dt^\beta \rangle = \eta^\alpha{}^\beta$. Given any manifold $M$ with metric $\langle ., . \rangle$ in general, flat coordinates can be found by solving the PDE in the following lemma for $n$-independent solutions

**Lemma 4.1.3 ([10, Section 2.1])** Suppose that a set of functions $\{t^\mu\}$ on $M$ forms coordinates over some open subset of $M$, then these coordinates are flat iff $\nabla dt^\mu = 0$.

**Proof:** The ( $\implies$ ) direction is trivial. For the converse, just write down $\nabla dt^\mu = 0$ in $t$ coordinates to get $\Gamma^\nu_{\nu\lambda} = 0$. Therefore in these coordinates, the metric compatibility condition gives $\partial_\lambda \eta_{\mu\nu} = 0$, thus $\eta_{\mu\nu}$ is constant.

For simplicity we will assume throughout that $\nabla E$ is diagonalizable. Therefore, in some appropriate flat coordinates, the Euler vector field and the unity vector field can be written as

$$E = \sum_{\alpha=1}^n (d_\alpha t^\alpha + r_\alpha) \frac{\partial}{\partial t^\alpha}, \quad e = \frac{\partial}{\partial t^1}.$$ Let us denote by $C_\alpha := \partial_\alpha : TM \to TM$ and $U := E : TM \to TM$ the endomorphism given by multiplication by $\partial_\alpha$ and $E$ respectively.

Note that $c$ plays the role of multiplicative structure constant on $T_1 \Sigma$ so we can write $\partial_\alpha \cdot \partial_\beta = c^\gamma_{\alpha\beta}(t) \partial_\gamma$ where $c^\gamma_{\alpha\beta}(t) = \eta^{\gamma\delta} c_{\alpha\beta}(t)$. The symmetry of $\nabla c$ from axiom A2 implies that there exists a locally defined function $F(t)$ such that $[11]$ Lemma 2.1

$$c_{\alpha\beta\gamma}(t) = \frac{\partial^3 F(t)}{\partial t^\alpha \partial t^\beta \partial t^\gamma}.$$ The function $F(t)$ is called the Frobenius potential of the Frobenius manifold and it satisfies the Witten-Dijkgraaf-Verlinde-Verlinde (WDVV) equations $[11, 10]$:

$$\frac{\partial^3 F}{\partial t^\alpha \partial t^\beta \partial t^\gamma} \eta^{\mu\nu} = \frac{\partial^3 F}{\partial t^\mu \partial t^\nu \partial t^\delta} \eta^{\alpha\beta} \frac{\partial^3 F}{\partial t^\gamma \partial t^\delta \partial t^\alpha},$$

which is equivalent to the associativity of multiplication in the Frobenius algebra. Additionally, axiom A3 implies that $EF = (3 - d)F + (at most quadratic terms)$. In general we call any function $F(t)$ such that $\sum_{\alpha=1}^n (d_\alpha t^\alpha + r_\alpha) \partial_\alpha F = (3 - d)F + (at most quadratic terms)$ for some $d_\alpha, r_\alpha, d \in \mathbb{C}$ a quasi-homogeneous function. Conversely, any function $F(t)$ on a metric vector space $(A, \langle ., . \rangle)$ satisfying the WDVV equation will define a structure of Frobenius manifold satisfying the axiom A1 and A2 but not A3. Additionally if $F(t)$ is quasi-homogeneous and $\partial_1 \partial_\alpha \partial_\beta F = \eta_{\alpha\beta}$ is the constant metric then axiom A3 will also be satisfied $[11]$ Lemma 2.1.

We define the operator

$$\mu := \frac{2 - d}{2} - \nabla E,$$

satisfying $\langle \mu x, y \rangle = - \langle x, \mu y \rangle$. Equivalently we can write this in flat coordinates as $\mu^\alpha := \frac{2 - d}{2} \delta^\alpha_\beta - \partial_\alpha E^\beta$. A Poisson bracket on $M$ can be given by

$$\{f, g\} := \langle df, \mu dg \rangle$$

for holomorphic functions $f, g$ on $M$.

**Definition 4.1.4 ([10, Section 2.3])** Let $\lambda \in \mathbb{C} \setminus \{u^1, \cdots, u^n\}$ where $u^i$ are eigenvalues of $\mathcal{U}$. A $\lambda$-flat pencil on a Frobenius manifold $M$ is a symmetric bilinear form $\langle ., . \rangle_\lambda$ given by $\langle \xi, \eta \rangle_\lambda := i_{E - \lambda e} \xi \cdot \eta$ for $\xi, \eta \in T^*_\lambda M$.

The multiplication between two cotangent vectors is induced from the multiplication of tangent vectors via the duality $\langle ., . \rangle_\lambda : T_\lambda M \to T^*_\lambda M$. We denote the components of this bilinear form by $g^{\alpha\beta}(\lambda) = \langle dt^\alpha, dt^\beta \rangle_\lambda$.

**Remark 4.1.5** When $\lambda = 0$, the $\lambda$-flat pencil $\langle ., . \rangle_\lambda := \langle ., . \rangle_0$ is known as the intersection form. It is easy to see that $\langle ., . \rangle_\lambda := \langle ., . \rangle - \lambda \langle ., . \rangle_\lambda$.

Let $\Sigma_\lambda \subset M$ be the region where $g^{\alpha\beta} - \lambda\delta^\alpha_\beta$ is not invertible. We define $M_\lambda(\lambda) := M \setminus \Sigma_\lambda$ and set a multiplication on $T_\lambda M_\lambda(\lambda)$ to be $x \ast_\lambda y := (U - \lambda)^{-1}(x \cdot y)$ for $x, y \in T_\lambda M_\lambda$. We denote the Levi-Civita connection of the metric $\langle ., . \rangle_\lambda$ by $\nabla^\lambda$. The manifold $(M_\lambda, \langle ., . \rangle_\lambda)$ together with $\ast_\lambda$ multiplication satisfies all the Frobenius manifold’s axioms except A3, in particular, we may not have $\nabla^\lambda = 0$. Therefore we call $M_\lambda(\lambda)$ the dual (almost) Frobenius manifold $[10]$ Proposition 3.1. Similarly, we can find a potential $F_\ast(\lambda)$ for $M_\lambda(\lambda)$ that gives $\ast_\lambda$ multiplication.
Now we can define a new affine flat, torsion-free connection called the deformed flat connection $\tilde{\nabla}^\lambda$ on $M_\ast(\lambda) \times \mathbb{C}^*$ by

$$\tilde{\nabla}^\lambda y = \nabla^\lambda y + \nu x \ast_\lambda y, \quad \tilde{\nabla}^\lambda \frac{\partial}{\partial y} = \partial_{y} + E \ast_\lambda \mu y, \quad x, y \in TM_\ast(\lambda), \nu \in \mathbb{C}^*$$

and $\tilde{\nabla}^\lambda \frac{\partial}{\partial \nu} = \tilde{\nabla}^\lambda \frac{\partial}{\partial \nu} = 0$ (see \cite{[11] Proposition 2.1} and \cite{[10]}). Using Lemma \ref{4.1.3} with the deformed flat connection we call coordinates $\{x^1\}$ such that $\tilde{\nabla}^\lambda dx^1 = 0$ deformed flat coordinates for $(..)_\lambda$ on $M_\ast(\lambda) \times \mathbb{C}^*$ and flat coordinates for $(..)_\lambda$ on $M_\ast(\lambda)$ when $\nu = 0$. We call any function $x = x(t; \nu; \lambda)$ satisfying $\tilde{\nabla}^\lambda dx(t; \nu; \lambda) = 0$ a $(\nu, \lambda)$-period.

**Proposition 4.1.6** (\cite{[10] Lemma 4.1}) Let $\xi = \xi_\alpha dt^\alpha := dx \in T^* M_\ast$ then the equation $\tilde{\nabla}^\lambda dx = 0$ can be written explicitly as

$$\partial_{\alpha} \xi \cdot (U - \lambda) = \xi \left( \mu + \nu + \frac{1}{2} \right) C_{\alpha}$$

with local $n$-linearly independent solutions $\xi^1, \ldots, \xi^n$ where each $\xi^i$ is closed. Hence we can find a set of $n$ independent functions $\{x^1(t; \nu; \lambda), \ldots, x^n(t; \nu; \lambda)\}$ such that $\xi^i = dx^i$ giving a local deformed flat coordinate system for $(..)_\lambda$ on $M_\ast(\lambda) \times \mathbb{C}^*$ when $\nu \neq 0$ and a local flat coordinate system for $(..)_\lambda$ on $M_\ast(\lambda)$ when $\nu = 0$.

**Proof:** It is straightforward to derive (4.2) from $\tilde{\nabla}^\lambda dx = 0$ and the definition of $\tilde{\nabla}^\lambda$.

When $\nu = 0$ the system of PDEs is compatible due to the vanishing of the Riemann curvature tensor and the torsion-freeness of the connection (see also (5.11)-(5.12) of \cite{[11]}) and therefore the local existence of $n$-linearly independent solutions $\xi^1, \ldots, \xi^n$ is guaranteed by the Frobenius theorem. Obviously, $\xi^i$ are closed 1-forms by the symmetry $c_{\gamma \beta}^\alpha = c_{\beta \alpha}^\gamma \Rightarrow \partial_{\alpha} \xi_\beta \equiv \partial_{\beta} \xi_\alpha$, therefore we can find $n$-independent functions $x^1(t), \ldots, x^n(t)$ as claimed.

The proof is similar when $\nu \neq 0$. $\square$

We note that $x(t; \nu; \lambda) = x(t^1 - \lambda, t^2, \ldots, t^n; \nu; 0)$ since $U \mapsto U - \lambda$ if $t^1 \mapsto t^1 - \lambda$. Therefore, it is sufficient to only consider the case $\lambda = 0$ and we call $x(t; \nu) := x(t; \nu; 0)$ simply a $\nu$-period. When $\nu = \frac{1}{2}$ a solution $x(t; \nu)$ is called an odd period. The important property is that given any two odd periods $\omega_1, \omega_2$, their Poisson bracket $\{\omega_1, \omega_2\}$ is constant. This will be useful later in defining a system of canonical coordinates on a certain symplectic manifold.

Let us close this section by introducing the notion of semi-simplicity and canonical coordinates of a Frobenius manifold.

**Definition 4.1.7** (\cite{[10] [11] [9]}) A point $t \in M$ is called semi-simple if $T_t M$ is a semi-simple algebra, $T_t M \cong \mathbb{C} \oplus \cdots \oplus \mathbb{C}$. A Frobenius manifold $M$ is semi-simple if the set of semi-simple points is dense in $M$.

**Lemma 4.1.8** (\cite{[10] [11] [9]}) Let $M$ be a semi-simple Frobenius manifold. Then a point where the eigenvalues $\{u^1, \cdots, u^n\}$ of $U$ are all distinct is a semi-simple point and the set $M_\text{ss} \subseteq M$ of all such points is dense in $M$. The set $\{u^1, \cdots, u^n\}$ is known as canonical coordinates on $M_\text{ss} \subseteq M$ and $\frac{\partial}{\partial u^i} \cdot \frac{\partial}{\partial u^j} = \delta_{ij} \frac{\partial}{\partial u^i}$.

### 4.2 Examples of Frobenius Manifolds

#### 4.2.1 1-dimensional Frobenius Manifold

The simplest example of a Frobenius manifold is $M = \mathbb{C} = t \in \mathbb{C}$. The multiplication on $T_t M$ is given by the trivial Frobenius algebra $\frac{\partial}{\partial t} \cdot \frac{\partial}{\partial t} = \frac{\partial}{\partial t}$. We also define the metric by $\langle \frac{\partial}{\partial t}, \frac{\partial}{\partial t} \rangle = 1$. It is easy to see that the Frobenius potential is $F(t) = \frac{1}{t} \beta^3$ and the Euler vector field is $E = t \frac{\partial}{\partial t}$.

#### 4.2.2 The Quantum Cohomology $QH^*(\mathbb{P}^1)$

Let $X$ be a projective algebraic variety. Loosely speaking, given $\gamma_i \in H^*(X, \mathbb{Q})$, a Gromov-Witten Invariant \cite{28} \cite{23}

$$GW_{\mathfrak{g}, n}(\gamma_1, \cdots, \gamma_n) := \int_{[\mathfrak{g}(X, \beta)]^{vir}} \prod_{i=1}^n ev^*_i \gamma_i \in \mathbb{Q}$$
counts the number of genus $g$ irreducible nodal curves with homology class $\beta \in H_2(X, \mathbb{Z})$ intersecting cycles $\gamma_i \cap [X] \in H_4(X, \mathbb{Q})$ at general positions. Here, $M_{g,n}(X, \beta)$ is the moduli space of stable maps $f : (C, x_1, \ldots, x_n) \to X$, and $ev_i : M_{g,n}(X, \beta) \to X$ is an evaluation map $ev_i(C, x_1, \ldots, x_n, f) = f(x_i)$. Suppose that $\{\gamma_1, \ldots, \gamma_n\}$ is a basis of $H^*(X, \mathbb{Q})$ then we define the genus $g$ Gromov-Witten potential to be the generating function

$$F_g(t) := \sum_{k=1}^{\infty} \frac{1}{k!} \sum_{\gamma_1, \ldots, \gamma_k \in \{1, \ldots, n\}} \sum_{\beta \in H_2(X, \mathbb{Z})} GW_{g,k}^{X,\beta}(\gamma_1, \ldots, \gamma_k) t_1^1 \cdots t_k^k.$$ 

It can be shown that the genus zero Gromov-Witten potential $F_0(t)$ satisfies the WDVV equations. Therefore we can define a Frobenius manifold $M = \{(t^1, \ldots, t^n) \in \mathbb{C}^n\}$ equip with metric $\eta_{ab} = \langle \gamma_a, \gamma_b \rangle = \int_X \gamma_a \cup \gamma_b$ and the Frobenius potential given by the genus zero Gromov-Witten potential $F(t) = F_0(t)$. We have that $\{t^n\}$ is a system of flat coordinates on $M$. In particular, if $\gamma_1 := 1 \in H^0(X, \mathbb{Q})$ then $e = \frac{\partial}{\partial t^1}$ is the multiplicative identity. It can be shown that the Euler vector field is given by $E := \sum_{\gamma_1} (1 - \frac{\gamma_1}{2}) t^n \frac{\partial}{\partial t^n} + \sum_{\gamma_1} t^{2g-2} \frac{\partial}{\partial t^{2g-2}}$.

Let us consider the case where $X := \mathbb{P}^1$. The basis of $H_4(\mathbb{P}^1, \mathbb{Q})$ can be given by $\{\gamma_1 = 1, \gamma_2 = h\}$ where $h$ is the hyperplane class. Also, we note that $H_2(X, \mathbb{Z}) = \{dh \mid d \in \mathbb{Z}\} \simeq \mathbb{Z}$ we can think of $\beta$ as simply an integer in this case. The corresponding Frobenius manifold $QH^*(\mathbb{P}^1) := \{(t^1 = t, \ t^2 = s) \in \mathbb{C}^2\}$ is known as the Quantum Cohomology of $\mathbb{P}^1$. The Frobenius potential is $F(t, s) = \frac{1}{4} t^2 s + Q$ where $Q = e^h$, hence the multiplication on $T_{(t, s)} QH^*(\mathbb{P}^1)$ is

$$\frac{\partial}{\partial t} \cdot \frac{\partial}{\partial t} = \frac{\partial}{\partial t} \cdot \frac{\partial}{\partial s} = \frac{\partial}{\partial s} \cdot \frac{\partial}{\partial t} = Q \frac{\partial}{\partial t}.$$ 

In other words, as $\frac{\partial}{\partial t} \mapsto 1$, $\frac{\partial}{\partial s} \mapsto h$ is an isomorphism of algebras $T_{(t, s)} QH^*(\mathbb{P}^1) \cong \mathbb{C}[h]/(h^2 - Q)$. The Euler vector field is given by $E = t \frac{\partial}{\partial t} + 2 \frac{\partial}{\partial s}$.

### 4.2.3 $A_n$-Coxeter Frobenius Manifold

In the following, we consider an example of Frobenius manifolds arising from the Coxeter group $A_n$ acting on $V := \{x^1 + \cdots + x^{n+1} = 0\} \subset \mathbb{C}^{n+1}$. The space of orbits is $V/A_n = Spec(\mathbb{C}[y^1, \ldots, y^n])$ where $y^1, \ldots, y^n$ are symmetric polynomials in $x^1, \ldots, x^{n+1}$ of degree $n - \alpha + 2$ and let $M_{A_n} := \{y^1, \ldots, y^n\} \subset \mathbb{C}^{n} \setminus \Sigma \subset V/A_n$ be the non-singular locus (containing only orbits with maximal size). It turns out that there exists a unique Frobenius structure on $M_{A_n}$ such that the intersection form $(\cdot, \cdot)$ is induced from the Euclidean metric on $\mathbb{C}^{n+1}$.

Define the superpotential $\lambda (z; y) : \mathbb{P}^1 \to \mathbb{P}^1$ to be the polynomial

$$\lambda (z; y) := z^{n+1} + y^n z^{n-1} + \cdots + y^1 = (z - x^1) \cdots (z - x^{n+1}).$$

Then for $\partial', \partial''$, $\partial''' \in T_y M_{A_n}$ the flat metric and multiplication are given as follows

$$\langle \partial', \partial'' \rangle := \sum_{z, \lambda (z; y) = 0} Res_z \left( \frac{(\partial' \lambda (z; y)) (\partial' \lambda (z; y)) dz}{\lambda (z; y)} \right)$$

$$c (\partial', \partial'', \partial''') := \sum_{z, \lambda (z; y) = 0} Res_z \left( \frac{(\partial' \lambda (z; y)) (\partial' \lambda (z; y)) (\partial''' \lambda (z; y)) dz}{\lambda (z; y)} \right).$$

It is easy to check that the Frobenius algebra $T_{y} M_{A_n}$ is isomorphic to the algebra $\mathbb{C}[z]/(\lambda (z; y))$ under the isomorphism $\frac{\partial}{\partial z} \mapsto z^{k-1}$. A flat coordinates $\{t^n\}$ such that $\eta_{ab} = \langle \partial' \lambda, \partial' \lambda \rangle = \frac{1}{n+1} \delta_{\alpha + \beta, n+1}$, deg $t^n = \deg y^n$ can be given by $\eta_{\alpha \beta} := -\frac{n + 1}{n - \alpha + 1} Res_z \left( \lambda^{n+1} \frac{dz}{\lambda (z; y)} \right)$.

Using the flat coordinates the Euler vector field is expressed as $E := \sum_{\alpha = 1}^{\infty} \frac{n - \alpha + 1}{n + 1} \frac{\partial}{\partial z}$. By construction, the roots $\{x^1, \ldots, x^{n+1}\}$ are flat coordinates of the intersection form $(\cdot, \cdot)$. It is not hard to show that $y^1 = (dx^1, dx^2) = \delta^{ij} - \frac{1}{n+1}$ and so $g_{ij} = \delta_{ij} + 1$.

As an example, let us study the case when $n = 3$. We have $\lambda (z; y) = z^4 + y^2 z^2 + y^2 z + y^1$ and $t^1 := y^1 - \frac{1}{2} (y^1)^2, t^2 := y^2, t^3 = y^3$. On $T_y M_{A_n}$ we find that $\frac{\partial}{\partial z}$ is the multiplication identity and

$$\frac{\partial}{\partial t^1} \cdot \frac{\partial}{\partial t^1} = -\frac{1}{4} t^1 \frac{\partial}{\partial t^1} + \frac{\partial}{\partial t^3}, \quad \frac{\partial}{\partial t^2} \cdot \frac{\partial}{\partial t^3} = -\frac{1}{4} t^2 \frac{\partial}{\partial t^1} - \frac{1}{4} t^3 \frac{\partial}{\partial t^2}, \quad \frac{\partial}{\partial t^3} \cdot \frac{\partial}{\partial t^3} = \frac{1}{16} (t^1)^2 \frac{\partial}{\partial t^1} - \frac{1}{4} t^2 \frac{\partial}{\partial t^2}.$$ 

Therefore, the Frobenius potential is given by $F(t) := (t^1)^2 t^1 + (t^2)^2 6t^2 + (t^3)^2 24t^3 + (t^3)^6 240$.
4.3 Tensor Product Frobenius Manifolds

Suppose that we were given two Frobenius manifolds $M'$ and $M''$ with dimension $n'$ and $n''$ respectively. We say that an $n' n''$-dimensional Frobenius manifold $M$ is a tensor product of $M'$ and $M''$ if it satisfied some properties [11] page 83-84 and we write $M = M' \otimes M''$. We equip the tensor product manifold $M$ with flat coordinates $\{ \{ \alpha' \} | \alpha' = 1, \ldots, n' ; \alpha'' = 1, \ldots, n'' \}$. The Frobenius structure of $M$ is

\[(TM, (\), )) = (TM' \otimes TM'', (\), )''(\), )''\), \quad \epsilon = \frac{\partial}{\partial t'^{\alpha'}} \otimes \frac{\partial}{\partial t''^\beta''}, \quad (4.3)\]

and we define $\frac{\partial}{\partial t'^{\alpha'}} = \frac{\partial}{\partial t^\alpha} \otimes \frac{\partial}{\partial t''^\beta''}$. Let $\{ dt'^{\alpha'} \}$ be the dual basis defined by $dt'^{\alpha'}(\frac{\partial}{\partial t'^{\alpha'}}) = \delta^\alpha_{\alpha'}\delta''_{\beta''}$, it follows that $dt'^{\alpha'} = dt^\alpha \otimes dt''^\beta''$. Let $d'$ and $d''$ be the charges of $M'$ and $M''$ respectively, then the charge of the tensor product $M$ is $d = d' + d''$. The Euler vector field $E$ is given in term of the Euler vector fields $E' = \sum_\alpha (d'_\alpha t'^\alpha + r'_\alpha) \frac{\partial}{\partial t'^{\alpha'}}$ and $E'' = \sum_\alpha (d''_\alpha t''^\beta + r''_\alpha) \frac{\partial}{\partial t''^\beta''}$ by [22] Theorem 2.1.10:

\[E = \sum_\alpha,\alpha' (d'_\alpha + d''_\alpha - 1) \epsilon^{\alpha'^{\alpha'}} \frac{\partial}{\partial t'^{\alpha'}} + \sum_\alpha r'_\alpha \frac{\partial}{\partial t'^{\alpha'}} + \sum_\alpha r''_\alpha \frac{\partial}{\partial t''^\beta''}. (4.4)\]

It follows that the operator $\mu$ for $M$ is given by

\[\mu^\beta_{\alpha' \alpha''} = \frac{2 - d} 2 \delta^\beta_{\alpha' \alpha''} - \partial_{\alpha'} \partial_{\alpha''} \epsilon^\beta_{\alpha' \alpha''} = \frac 2 2 (d' + d'') \delta^\beta_{\alpha' \alpha''} - (d'_\alpha + d''_\alpha - 1) \delta^\beta_{\alpha' \alpha''} = \left( \frac{2 - d} 2 \delta^\beta_{\alpha' \alpha''} - (d'_\alpha + d''_\alpha) \delta^\beta_{\alpha' \alpha''} \right) \delta^\beta_{\alpha' \alpha''}, \]

or in a more compact notation

\[\mu = \mu' \otimes 1'' + 1' \otimes \mu''. \quad (4.5)\]

Let us denote the Poisson bracket on $M'$ and $M''$ by $(\), ')'$ and $(\), ')''$ respectively, then the Poisson bracket on $M = M' \otimes M''$ is

\[\{ t'^{\alpha'} , t''^\beta'' \} = \{ dt'^{\alpha'} , \mu dt''^\beta'' \} = \{ t'^{\alpha'}, t''^\beta'' \} \{ dt'^{\alpha'}, dt''^\beta'' \} = \{ t'^{\alpha'}, t''^\beta'' \}. \]

**Definition 4.3.1** ([10] Section 5.5) We call the locus $\{ t'^{\alpha'} = 0 \mid \alpha' \neq 1' \text{ or } \alpha'' \neq 1'' \} \subset M = M' \otimes M''$ the *coordinates cross* of $M$. Let $\{ t'^{\alpha'} \}$ and $\{ t''^{\alpha''} \}$ be flat coordinates of $M'$ and $M''$ respectively then $t'^{\alpha'} = t'^{\alpha'}, t''^{\alpha''} = t''^{\alpha''}$ and $t'^{1'\alpha''} = t'^{\alpha''}$ and $t''^{1''\alpha'} = t''^{\alpha'} = t''^{\alpha''}$ on coordinates cross. The coordinates cross is a nice place to work on the manifold $M$ because it is where we have an obvious splitting of $M$ back into $M'$ and $M''$. More concretely, suppose that $u = (t'^{\alpha'}) \in M$ is on a coordinates cross such that $(t'^{\alpha'}) = u' \in M'$ and $(t''^{\alpha''}) = u'' \in M''$, then $T_u M = T_{u'} M' \otimes T_{u''} M''$ and the multiplication splits in the sense that $(x \otimes w) \cdot (y \otimes z) := x \cdot y \otimes w \cdot z$, in other words, $C_{\alpha' \beta'}^\gamma \gamma'_{\alpha'' \beta''} = C_{\alpha' \beta'}^{\gamma' \gamma''_{\alpha'' \beta''}}$ or

\[C_{\alpha' \alpha''} = C_{\alpha'}^{\alpha''} \otimes C_{\alpha''}. \quad (4.6)\]

Moreover, the Euler vector field $E$ of $M$ simplifies to

\[E = E' \otimes \partial_{t'} + \partial_{t'} \otimes E'' - t' \partial_{t'} \otimes \partial_{t''}. \quad (4.7)\]

on coordinates cross.

**Remark 4.3.2** Away from the coordinates cross we are still going to have $T_u M = T_{u'} M' \otimes T_{u''} M''$ but the multiplication will be much more complicated and the points $u'$ and $u''$ will be non-trivial functions of $u = (t'^{\alpha'})$. The actual definition of the multiplication on $T_u M$ when $t$ is a generic point is given in [28] [22]. Let $\{ \Omega_{0,n} : (V')^n \otimes n H^* (\mathcal{M}_{0,n}, \mathbb{C}) \}$ and $\{ \Omega''_{0,n} : (V'')^n \otimes n H^* (\mathcal{M}_{0,n}, \mathbb{C}) \}$ be the genus zero Cohomological Field Theories (CohFTs) corresponding to the Frobenius manifolds $M'$ and $M''$. Then $M = M' \otimes M''$ is the Frobenius manifold corresponding to the cup product CohFT $\Omega_{0,n} := \Omega_{0,n} \cup \Omega''_{0,n} : (V \otimes V'')^n \otimes n H^* (\mathcal{M}_{0,n}, \mathbb{C})$. It is possible to check that the multiplication on $T_u M$ defined splits as expected when $t$ is on coordinates cross.
Let’s consider the case where \( M'' = QH^*(\mathbb{P}^1) \) and \( M' \) is an arbitrary \( n' \)-dimensional Frobenius manifold. The \( 2n' \)-dimensional Frobenius manifold \( M = M' \otimes QH^*(\mathbb{P}^1) \) has a Poisson structure \( \{ , \} \):

\[
\{ t^{\alpha} t'{}^{\beta}, t^{\alpha'} t'{}^{\beta'} \} = \eta^{\alpha\beta} \left( \mu'_\beta + \frac{1}{2} \right), \quad \{ t^{\alpha} t'{}^{\beta}, t^{\alpha'} t'{}^{\beta'} \} = \eta^{\alpha\beta} \left( \mu'_\beta - \frac{1}{2} \right).
\]

We will only get a symplectic structure on \( M \) if and only if \( \mu'_\alpha \neq -\frac{1}{2} \) for all \( \alpha = 1, \cdots, n' \) and in that case the symplectic form \( \Omega \) of \( M \) can be defined from the Poisson bracket \( \{ , \} \) to be

\[
\Omega = \sum_{n=1}^n \frac{dt^{\alpha} \wedge d(t^{\alpha'} + 1)t'{}^{\beta}}{\mu'_\alpha + \frac{1}{2}}.
\]

Proposition 4.1.6 guarantees that we can find a \( 2n' \)-independent odd periods \( \{ X^i(t^{\beta} t'{}^{\beta'}), Y_i(t^{\beta} t'{}^{\beta'}) \} \) on \( M_\ast \).

**Theorem 4.3.3 ([10, Theorem 5.16])** Let \( M := M' \otimes QH^*(\mathbb{P}^1) \) and let \( \{ x^1(t), \cdots, x^n(t) \} \) be a system of flat coordinates of the intersection form on \( M'_\ast \). Then there exists a locally defined system of \( 2n' \)-independent odd periods \( \{ X^i(t^{\beta} t'{}^{\beta'}), Y_i(t^{\beta} t'{}^{\beta'}) \} \) such that their restrictions on the coordinate cross of \( M_\ast \) is given by

\[
X^i(t, Q) = x^i(t) + O(Q), \quad Y_i(t, Q) = g_{ij}x^j(t)\log(Q) - 2\frac{\partial F'_i}{\partial x^j} + O(Q)
\]

where \( g_{ij} := (dx^i, dx^j) \) is a constant metric, \( F'_i \) is the Frobenius potential for \( M'_\ast \). Moreover the set of odd periods \( \{ X^i(t^{\beta} t'{}^{\beta'}), Y_i(t^{\beta} t'{}^{\beta'}) \} \) forms a canonical coordinates system for the symplectic structure on \( M_\ast \):

\[
\{ X^i, Y_j \} = \delta_{ij}, \quad \{ X^i, X^j \} = \{ Y_i, Y_j \} = 0.
\]

In other words, we have \( \Omega = \sum_{i=1}^n dx^i \wedge dy_i \).

**Proof:** We refer to the original material [10] Theorem 5.16 for proof.

We have a family of Lagrangian submanifolds of \( M \):

\[
L_s = \{ t^{1'2'} = s \text{ fixed}, t^{\alpha 2'} = 0, \alpha = 2, \cdots, r, t^{\beta 1''} = \text{arbitrary}, \beta = 1, \cdots, n' \} \subset M
\]

parameterized by the coordinate \( s \) (or equivalently, by \( Q = e^s \)). Because \( L_s \) is parameterized by the flat coordinates \( \{ t^{\alpha 1''}, t^{\beta 1''} \} \) of \( M' \) and if \( Q > 0 \) is sufficiently small \( \{ X^i \} \) will be a coordinates system for \( M'_\ast \), hence we can write \( L_s := \{ (X^1, \cdots, X^n, Y_1, \cdots, Y_{n'}) \} \mid Y_i = f_i(\{ X^k \}, Q) \} \) for some functions \( f_i, i = 1, \cdots, n' \). By the definition of Lagrangian submanifold, we have

\[
0 = \Omega|_{L_s} = \sum_{i=1}^{n'} dX^i \wedge df_i(\{ X^k \}, Q) = \sum_{i,j=1} dX^i \wedge \frac{\partial f_i}{\partial X^j} dX^j = \sum_{i,j=1} \left( \frac{\partial f_i}{\partial X^j} - \frac{\partial f_j}{\partial X^i} \right) dX^i \wedge dX^j.
\]

This implies the existence of the generating function \( S_{M'} = S_{M'}(\{ X^k \}, Q) \) of the Lagrangian submanifold such that

\[
Y_i = \frac{\partial S_{M'}(\{ X^k \}, Q)}{\partial X^i}.
\]

for all sufficiently small \( Q \). As we are going to see, if \( M' := M_{A_\eta} \) then \( X^i = a^i := \oint_{A_\eta} dS_{SW}, Y_i = b_i := \oint_{B_i} dS_{SW} \) and \( S_{M_{A_\eta}} = 2\pi i \overline{S}_{SW} \). So the Seiberg-Witten theory can be encoded into a certain tensor product of Frobenius manifolds.

### 4.4 Odd Periods of \( M \otimes QH^*(\mathbb{P}^1) \) and Seiberg-Witten Theory

In this section, we study the tensor product Frobenius manifold \( M \otimes QH^*(\mathbb{P}^1) \) and its relations to the Seiberg-Witten theory when \( M := M_{A_\eta} \) as noted in [10].
4.4.1 Odd Periods of $M \otimes QH^*(\mathbb{P}^1)$ as period integrals

First, we will consider the general case when $M$ is an arbitrary $n$-dimensional Frobenius manifold. Without loss of generality, we will assume that the intersection form $g^{\alpha \beta}$ is invertible on $M$ (we only need to replace $M$ by $M_e := M \setminus \Sigma$ otherwise). Let us consider Equation (4.12) on the coordinates cross of $M \otimes QH^*(\mathbb{P}^1)$. Setting $\lambda = 0, u = \frac{1}{2} \xi = \xi(t, \lambda) := p_0(t, Q) dt^\alpha \otimes dt + q_0(t, Q) dt^\alpha \otimes ds$ and $p := p_0 dt^\alpha, q := q_0 dt^\alpha$ then the $\alpha \alpha'' = \alpha_1, \alpha = 1, \cdots, n$ and $\alpha \alpha'' = 12$ parts of Equation (4.12) yields

\[
\begin{align*}
\partial_\alpha p \cdot u + 2 \partial_\alpha q &= p \left( \mu - \frac{1}{2} \right) C_\alpha, \\
\partial_\alpha q \cdot u + 2 Q \partial_\alpha p &= q \left( \mu + \frac{1}{2} \right) C_\alpha
\end{align*}
\]

(4.10)

for $\alpha = 1, \cdots, n$. We note that only the $\alpha \alpha'' = \alpha_1, \alpha = 1, \cdots, n$ and $\alpha \alpha'' = 12$ parts will be relevant on the coordinate cross.

**Proposition 4.4.1 ([10], Proposition 5.18)** Let $x(t)$ be a solution to the intersection form flat coordinate equation on $M_{\alpha}$. Then for an arbitrary closed contour $C$, on a Riemann surface where the integrand is defined,

\[
p_\alpha = \oint_C \frac{\partial_\alpha x(t^1 - \lambda, t^2, \cdots, t^n)}{\sqrt{\lambda^2 - 4Q}}, \quad q_\alpha = -\frac{1}{2} \oint_C \frac{\lambda \partial_\alpha x(t^1 - \lambda, t^2, \cdots, t^n)}{\sqrt{\lambda^2 - 4Q}}
\]

(4.11)

satisfies the system of equations (4.10). It follows that

\[
\omega(t, Q) = \oint_C \frac{x(t^1 - \lambda, t^2, \cdots, t^n)}{\sqrt{\lambda^2 - 4Q}} d\lambda
\]

(4.12)

is an odd period on the coordinates cross of $M \otimes QH^*(\mathbb{P}^1)$. 

**Proof:** It is straightforward to substitute $p$ and $q$ given by (4.11) into (4.10) and show that every equation is satisfied using the fact that $\xi = \xi(t; \lambda) := dx(t^1 - \lambda, t^2, \cdots, t^n) = dx(t; 0; \lambda)$ satisfies

\[
\partial_\alpha \xi \cdot (u - \lambda) = \xi \left( \mu - \frac{1}{2} \right) C_\alpha.
\]

Let $\bar{\omega} = \bar{\omega}(\{t^\alpha \alpha''\})$ be an odd period on $M \otimes QH^*(\mathbb{P}^1)$. We can write in general:

\[
\bar{\omega} = \omega(t, Q) + O(t^{\alpha > 1.2})
\]

where $O(t^{\alpha > 1.2})$ contains all terms depending on the coordinates $t^{22}, \cdots, t^{n2}$ which we do not need to care about because they will vanish on the coordinates cross. Let $\omega(t, Q)$ be given by (4.12) then

\[
p_\alpha = \frac{\partial \omega}{\partial t^{\alpha}} = \oint_C \frac{\partial_\alpha x(t^1 - \lambda, t^2, \cdots, t^n)}{\sqrt{\lambda^2 - 4Q}} d\lambda = \oint_C \frac{\xi_\alpha}{\sqrt{\lambda^2 - 4Q}} d\lambda
\]

\[
qu_\alpha = \frac{\partial \omega}{\partial t^{\alpha}} = -\frac{1}{2} \oint_C \frac{x(t^1 - \lambda, t^2, \cdots, t^n)}{\sqrt{\lambda^2 - 4Q}} \frac{4Q}{(\lambda^2 - 4Q)^{3/2}} d\lambda
\]

\[
= \frac{1}{2} \oint_C x(t^1 - \lambda, t^2, \cdots, t^n) \frac{\partial}{\partial \lambda} \left( \frac{\lambda}{\sqrt{\lambda^2 - 4Q}} \right) = \frac{1}{2} \oint_C \frac{\lambda \xi_\alpha}{\sqrt{\lambda^2 - 4Q}} d\lambda
\]

This completes the proof of the Proposition.

The following proposition make it more precise how to obtain from period integrals, a complete linearly independ-ent set of odd periods, that forms canonical coordinates for the symplectic structure on the coordinate cross of $M \otimes QH^*(\mathbb{P}^1)$:

**Proposition 4.4.2** Let $M$ be a semisimple Frobenius manifold and let $\{u^1, \cdots, u^n\}$ be canonical coordinates. Let $\{x^1, \cdots, x^n\}$ be flat coordinates of the intersection form $(\_ \_ \_ \_)$ on $M$, chosen such that the monodromy of $x^i$ at $\lambda = u^i$ is $x^i \leftrightarrow -x^i$, $g^{ij} = (dx^i, dx^j), (g_{ij}) = (g^{ij})^{-1}$ and $x_i := g_{ij} x_j, \xi_i(t; \lambda) := g_{ij} \xi_j(t; \lambda)$. We define $A$ to be a cycle enclosing singularities $\pm 2\sqrt{Q}$ and $B_i$ to be a cycle enclosing $-2\sqrt{Q}$ and $u^i$. Then the following odd period integrals

\[
X^i(t, Q) := \frac{1}{2\pi i} \oint_A x^i(t^1 - \lambda, t^2, \cdots, t^n) d\lambda, \quad Y_i(t, Q) := \sum_{j=1}^n g_{ij} \oint_{B_j} x^j(t^1 - \lambda, t^2, \cdots, t^n) d\lambda
\]

(4.13)

gives a complete linearly independent set of odd periods $\{X^{i=1, \cdots, n}, Y_{i=1, \cdots, n}\}$ that forms canonical coordinates for the symplectic structure on the coordinate cross of $M \otimes QH^*(\mathbb{P}^1)$ in the sense of Theorem 4.3.3.
4.4. Odd Periods of $M \otimes QH^*(\mathbb{P}^1)$ and Seiberg-Witten Theory

The cycles $A$ and $B_i$ can be thought of as cycles on a non-compact Riemann surface $\Lambda_i$ constructed by gluing two copies of $\mathbb{C} \setminus \cup_{i=1}^n L_i$ along the cut $[-2\sqrt{Q}, +2\sqrt{Q}]$ and $L_i$. Rays $L_1, \ldots, L_n$ are defined in the usual way

$$L_i = \{ u^i + \rho e^{i\theta} | \rho \in \mathbb{R}_+ \}. \quad (4.14)$$

**Proof:** To avoid confusion with the established result in Theorem [4.3.3] we shall define

$$\tilde{X}^i(t, Q) := \frac{1}{2\pi i} \int_A \frac{x^i(t^1 - \lambda, t^2, \ldots, t^n)}{\sqrt{\lambda^2 - 4Q}} d\lambda, \quad \tilde{Y}_i(t, Q) := \frac{1}{2\pi i} \int_{B_i} \frac{x^i(t^1 - \lambda, t^2, \ldots, t^n)}{\sqrt{\lambda^2 - 4Q}} d\lambda \quad (4.15)$$

and $\tilde{Y}_i := g_{ij} \tilde{Y}^j$. From Proposition [4.4.1] we know that the given integral expressions for $\tilde{X}^i(t, Q)$ and $\tilde{Y}_i(t, Q)$ will be odd periods on the coordinate cross of $M \otimes QH^*(\mathbb{P}^1)$. A complete linearly independent set of odd periods $\{\tilde{X}^i, \tilde{Y}_i\}$ will always forms coordinates such that the Poisson bracket $\{\cdot, \cdot\}$ is constant. Therefore we can always form an appropriate linear combination of a given odd period system to obtain canonical coordinates $\{X^i, Y^j\} = \{Y_i, Y_j\} = 0, \{X^i, Y_j\} = \delta^i_j$. Therefore we only have to show that the set $\{\tilde{X}^i(t, Q), \tilde{Y}_i(t, Q)\}$ as defined above is linearly independent and already are canonical coordinates without the need of forming any further linear combinations. Note that canonical coordinates are not unique, any transformation of $\{\tilde{X}^i, \tilde{Y}_i\}$ via an action of $Sp(2n, \mathbb{C})$ will remain canonical.

Since $\{\tilde{X}^i, \tilde{Y}^j\}, \{\tilde{Y}_i, \tilde{Y}_j\}$ and $\{\tilde{X}^i, \tilde{Y}_j\}$ are constants, we can evaluate them in the limit $Q \to 0$. We will need the following:

$$p_{\tilde{X}^i, \alpha} := \frac{\partial \tilde{X}^i}{\partial \alpha \lambda}, \quad q_{\tilde{X}^i, \alpha} := \frac{\partial \tilde{X}^i}{\partial \alpha \lambda} \lambda, \quad p_{\tilde{Y}_i, \alpha} := \frac{\partial \tilde{Y}_i}{\partial \alpha \lambda}, \quad q_{\tilde{Y}_i, \alpha} := \frac{\partial \tilde{Y}_i}{\partial \alpha \lambda} \lambda,$$

where $\xi^i = \xi^i(t; \lambda) d\lambda := dx^i(t^1 - \lambda, t^2, \ldots, t^n)$. Similarly, we define $p_{\tilde{Y}_i, \alpha} := \partial \tilde{Y}_i/\partial \alpha \lambda$, and $q_{\tilde{Y}_i, \alpha} := \partial \tilde{Y}_i/\partial \alpha \lambda$. As $Q \to 0$ we have

$$p_{\tilde{X}^i} = \xi^i(t) + O(Q), \quad q_{\tilde{X}^i} = O(Q).$$

From this we conclude that $\tilde{X}^i$ are indeed $X^i, i = 1, \ldots, n$ in Theorem [4.3.3]. To study $p_{\tilde{Y}_i}$ and $q_{\tilde{Y}_i}$ as $Q \to 0$, first we will deform $B_i$ so that $\tilde{f}_{B_i} = \int_{u^i}^{u^i + 2\sqrt{Q} \alpha} - \int_{u^i}^{u^i} = 2 \int_{u^i}^{u^i} d\alpha$. The last equality follows because these integrals are on the different sheets of $\Lambda_i$, hence $x^i$ switches sign crossing $L_i$ whereas $\sqrt{\lambda^2 - 4Q}$ switches sign crossing $[-2\sqrt{Q}, +2\sqrt{Q}]$. It is important to deform $B_i$ to this specific path because $B_i$ must intersects the segment $[-2\sqrt{Q}, +2\sqrt{Q}]$ by definition and the deformed path will ensure this condition is met as $Q \to 0$. We have

$$p_{\tilde{Y}_i} = 2 \int_{u^i}^{u^i + 2\sqrt{Q}} \xi^i(t^1 - \lambda, t^2, \ldots, t^n) d\lambda = 2 \xi^i(t) \int_{u^i}^{u^i + 2\sqrt{Q}} \frac{d\lambda}{\sqrt{\lambda^2 - 4Q}} + 2 \sum_{k=1}^{\infty} \frac{\partial \xi^i(t)}{\partial \lambda} \left( \frac{1}{2} \right)^k \int_{u^i}^{u^i + 2\sqrt{Q}} \frac{(\lambda - \mu)^k d\lambda}{\sqrt{\lambda^2 - 4Q}}$$

$$= \xi^i(t) \log Q + R_i(t) + O(Q).$$

Where we let $R_i(t)$ be the $O^0$ terms of the small $Q$ expansion above. Similarly, we have

$$q_{\tilde{Y}_i} = - \int_{u^i}^{u^i} \lambda \xi^i(t; \lambda) d\lambda = - \int_{u^i}^{u^i} \xi^i(t; \lambda) d\lambda + O(Q)$$

$$= - \int_{u^i}^{u^i} \xi^i(t; \lambda) - \left( \mu + \frac{1}{2} \right)^{-1} d\lambda + O(Q)$$

where the last equality is due to

$$\partial \lambda \xi^i(t; \lambda) \cdot (U - \lambda) = - \xi^i(t; \lambda) \left( \mu + \frac{1}{2} \right) \Rightarrow \partial \lambda (\xi^i(t; \lambda) \cdot (U - \lambda)) = - \xi^i(t; \lambda) \left( \mu + \frac{1}{2} \right).$$

According to [10], Lemma 4.4 combining with [10] Equation (4.3) we can write $\xi^i(t; \lambda), i = 1, \ldots, n$ in canonical coordinates near $\lambda = u^i$ as

$$\xi^i(t; \lambda) = \sum_{k=0}^{n} \frac{1}{u^i(t) - \lambda} \left( \delta_{1} + O(u^i(t) - \lambda) \right) d\lambda^k.$$
Using the fact that $U = \text{diag}(u^1, \ldots, u^n)$ in canonical coordinates, we conclude: $\lim_{\lambda \to u^i} \xi^i(t; \lambda) \cdot (U - \lambda) = 0, i = 1, \ldots, n$. Therefore,

$$q_{Y^i} = \xi^i(t) \cdot U \left( \mu + \frac{1}{2} \right)^{-1} - \lim_{\lambda \to u^i} \xi^i(t; \lambda) \cdot (U - \lambda) \left( \mu + \frac{1}{2} \right)^{-1} + O(Q)$$

$$= \xi^i(t) \cdot U \left( \mu + \frac{1}{2} \right)^{-1} + O(Q).$$

Applying $g_{ij}$ to lowering the indices, we can see that the gradients of $\tilde{Y}_i(t, Q)$ as $Q \to 0$ is given by

$$(p_{\tilde{Y}^i}, q_{\tilde{Y}^i}) = \left( \xi_i(t) \log Q + \tilde{r}_i(t), \xi_i(t) \cdot U \left( \mu + \frac{1}{2} \right)^{-1} + O(Q), \quad \tilde{r}_i(t) := g_{ij} F^j(t). \right) \quad (4.16)$$

As a solution of odd period equations, $\tilde{Y}_i(t, Q)$ can be expressed as a linear combination of a complete set of linearly independent odd periods $\{X^i, Y^i\}$ in Theorem 4.3.3. From the leading term of $p_{\tilde{Y}^i}$ we deduce that $\tilde{Y}_i = Y_i + \sum_{k=1}^n c_{ik} X^k$ where $c_{ik}$ are some constants. Recall from the proof of Theorem 5.16, it was assumed that $p_{\tilde{Y}^i}$ takes the form $p_{\tilde{Y}^i} = \xi_i(t) \log Q + r_i(t) + O(Q)$ where $r_i(t) = \sum_{k=1}^n A_{ik}(t) \xi^k(t)$ and $A_{ik}(t)$ is a function to be determined. Then using odd period equations and $q_{\tilde{Y}^i} = \xi_i(t) \cdot U \left( \mu + \frac{1}{2} \right)^{-1} + O(Q)$ we found that

$$r_{i,\alpha}(t) = -\frac{\partial}{\partial t^\alpha} F_i(t)$$

where $F_i(t)$ is the potential of dual (almost) Frobenius manifold $M_\alpha$. By differentiating $\tilde{Y}_i = Y_i + \sum_{k=1}^n c_{ik} X^k$ and comparing terms, we find that $\tilde{r}_i(t) = \sum_{k=1}^n (A_{ik}(t) + c_{ik}) \xi^k(t)$. Since we have $q_{\tilde{Y}^i} = \xi_i(t) \cdot U \left( \mu + \frac{1}{2} \right)^{-1} + O(Q)$, the same proof as in Theorem 4.3.3 applies once again and we conclude that $\tilde{r}_i(t)$ takes the same form as $r_i(t)$ with a new potential $F_i(t) = F_i(t) + (\text{quadratic terms})$. Due to the form of gradients $(p_{\tilde{Y}^i}, q_{\tilde{Y}^i})$ and $(p_{\tilde{X}^i}, q_{\tilde{X}^i})$, the evaluation of Poisson brackets in the limit $Q \to 0$ is now no different from the remaining of the proof of Theorem 4.3.3. It follows that $\{\tilde{X}^i, \tilde{X}^j\}, \{\tilde{Y}_i, \tilde{Y}_j\} = 0$ and $\{\tilde{X}^i, \tilde{Y}_j\} = \delta^i_j$. We can now remove the tilde if we wished and the proposition is proven. \hfill \Box

**Example 4.4.3** Recall that in the case where $M$ is 1-dimensional we have $x(t - \lambda) = 2\sqrt{t - \lambda}$, therefore the monodromy is just a reflection $+x \leftrightarrow -x$ when $\lambda$ moves around $t$. In this case the integral

$$X(t, Q) = \int_C \frac{\sqrt{t - \lambda}}{\sqrt{\lambda^2 - 4Q}} d\lambda$$

is done on a genus 1 Riemann surface: $y^2 = (t - \lambda)(\lambda^2 - 4Q)$ which is a double cover of $\lambda$-plane $\cong \mathbb{C}$. The integral over cycles $A$ and $B = B_1$ simply compute the $A$ and $B$-periods of $\sqrt{\lambda^2 - 4Q} d\lambda$.

For a general Frobenius manifold $M$ since for a fixed $(t^1, \ldots, t^n)$, the flat coordinate $x^i(t^1, \lambda, t^2, \ldots, t^n)$ has monodromies at $\lambda = u^1, \ldots, u^n$, where $u^i = u^i(t^1, \ldots, t^n)$ are the canonical coordinates of $M$. Using [10, Equation (4.55)]:

$$x^i(t^1 - \lambda, t^2, \ldots, t^n) = \frac{2}{1 - d} \sum_{k=1}^n (u_k(t) - \lambda) \sqrt{\frac{\partial}{\partial u^k} \frac{\partial}{\partial u^k} \phi_k^{(i)}(t; \lambda)}$$

where $\phi_k^{(i)} := \frac{\xi_i}{\sqrt{\eta^i \eta^j}} \phi_k^i d\eta^i$ and the application of [10, Lemma 4.5] with $\nu = 0: M_f \xi^i = \xi^i - 2\epsilon^{ij} \xi^j$ (no summation over repeated indices), where $\epsilon^{ij} = \frac{\eta^i}{\sqrt{\eta^i \eta^j}}$, we conclude that the monodromy of $x^i$ at $u^j$ is given by (no summation over repeated indices):

$$x^i \mapsto M_f x^i = x^i - 2\epsilon^{ij} x^j.$$ 

It is clear that the monodromy of $x^i$ at $\lambda = u^i$ is $x^i \mapsto M_f x^i = -x^i$ because $\epsilon^{ii} = 1$, satisfying the assumption of Proposition 4.4.2. Unlike what we have seen in the Example 4.4.3, a double cover of $\lambda$-plane is in general not sufficient to define a single-valued $x^i(t^1 - \lambda, t^2, \ldots, t^n)$. We can see this from a monodromy of $x^k$ around $u^i$ follows by a monodromy around $u^j$

$$x^k \mapsto M_{ij} x^k = x^k - 2\epsilon^{ik} x^j \mapsto M_{ij} x^k - 2\epsilon^{ik} M_{jk} x^j = x^k - 2\epsilon^{ik} x^j - 2\epsilon^{ik} x^j + 4\epsilon^{ij} \epsilon^{ik} x^j.$$ 

This is not $x^k$ unless $i = j$ suggesting that we potentially need an infinite cover of $\lambda$-plane.
4.4.2 The tensor product Frobenius manifold $M_{A_b} \otimes QH^*(\mathbb{P}^1)$ and Seiberg-Witten Theory

Let us specialize to the case where $M = M_{A_b}$, where we recall from Section 4.2.3 that the $A_b$-Coxeter Frobenius manifold $M_{A_b}$ is defined by the superpotential $\lambda(z; y) = z^{g+1} + y^g z^{g-1} + \cdots + y = (z - x^i)(z - x^{g+1})$. The flat coordinates for $(\ldots)$ on $M_{A_b}$ can be found and we denote them as $(t^1, \ldots, t^g)$, $\deg_t t^i = \deg y^g$ while $(x^1, \ldots, x^{g+1})$ are flat coordinates of the intersection form $(\ldots)$ of $M_{A_b}$. In other words, for a fixed $(t^1, \ldots, t^g)$, the polynomial $\lambda(z; t)$ has $(g + 1)$-roots $\{x^{i_1}, \ldots, x^{i_{g+1}} = x^i(t^1, \ldots, t^n)\}$, each of them will satisfy the intersection form flat coordinates equations on $M_{A_b}$, but only $g$ of them will be linearly independent because of the relation $x^1 + \cdots + x^{g+1} = 0$.

More generally, $\{x^{i_1}, \ldots, x^{i_g}(1; 0; \lambda) := x^i(t^1 - \lambda, t^2, \ldots, t^g)\}$ are flat coordinates of the $\lambda$-flat pencil $(\ldots)$. Since $t^1 = y^i$, it is clear that $\lambda(x^i(t^1 - \lambda, t^2, \ldots, t^g); t) = \lambda, \forall i, 1, g + 1$. In other words, $x^i(t^1; 0; \lambda)$ are locally an inverse of $\Lambda = \lambda(z; t)$. The canonical coordinates of $M_{A_b}$ are given by the critical values $\{u^1, \ldots, u^g\}$ of $\lambda(z; t)$. Suppose that $x^i(t^1 - u^1, t^2, \ldots, t^g) = x^{i+1}(t^1 - u^1, t^2, \ldots, t^g)$ then the monodromy $M_i$ around $\Lambda = u^i$ is given by $M_i x^i = x^{i+1}, M_i x^{i+1} = x^i$ for $i = 1, \ldots, g$ and $M_i x^j = x^j$ for all $j \neq i, i + 1$.

Remark 4.4.4 We may take the flat coordinates of $M_{A_b}$ to be $\{x^{i_1}, \ldots, x^{i_g} := x^i - x^{i+1}\}$ for the assumption $M_i x^i = -x^i$ of Proposition 4.4.2 to be satisfied.

Now, let us turn our attention to finding the odd periods on the coordinate cross of $M_{A_b} \otimes QH^*(\mathbb{P}^1)$. Since the superpotential $\Lambda = \lambda(x; t)$ is really simple in our case, instead of considering the integral on $A_i$, we will reserve the notation to be

$$
\omega(t, Q) = \oint_C dS_{SW}
$$

is an odd period on the coordinate cross of $M \otimes QH^*(\mathbb{P}^1)$ for any cycle $C \in H_1(\Sigma_g, \mathbb{C})$.

Proposition 4.4.5 (See also, [10, Example 2]) Let us choose $A$ and $B$-periods on the Seiberg-Witten curve $\Sigma_g$ as in Figure 4.4.2 Then

$$
X^i(t, Q) = \frac{1}{2\pi i} \int_{A_i} dS_{SW}, \quad Y_i(t, Q) = b_i := \int_{B_i} dS_{SW}, \quad i = 1, \ldots, g
$$

gives a complete linearly independent set of odd periods $\{X^{i_1}, \ldots, X^{i_g}, Y_1, \ldots, Y_g\}$ that forms canonical coordinates for the symplectic structure on the coordinates cross of $M_{A_b} \otimes QH^*(\mathbb{P}^1)$ in the sense of Theorem 4.3.3. Additionally, if $X^{i+1}(t, Q) := \frac{1}{2\pi i} \int_{A_{i+1}} dS_{SW}$ then $X^1 + \cdots + X^g + X^{g+1} = 0$.

Proof: We already know from Proposition 4.4.1 that the given integral expressions are odd periods on the coordinate cross of $M_{A_b} \otimes QH^*(\mathbb{P}^1)$. To avoid confusion with the established result in Theorem 4.3.3 we define $\tilde{X}^i := \frac{1}{2\pi i} \int_{A_i} dS_{SW}, \tilde{Y}_i := \int_{B_i} dS_{SW}$ and we will reserve the notation $\{X^i, Y_i\}$ for odd periods canonical coordinates according to Theorem 4.3.3 for now. Changing the integration variable back from $x$ to $\lambda$, we have

$$
\tilde{X}^i(t, Q) = \frac{1}{2\pi i} \int_{A_i} dS_{SW} = \frac{1}{2\pi i} \int_{A} x^i(t^1 - \lambda, t^2, \ldots, t^g) d\lambda.
$$


A genus \( g \) Seiberg-Witten curve \( \Sigma_g \) with a particular choice of \( A \) and \( B \)-cycles which generates \( H^1(\Sigma_g, \mathbb{C}) \) such that \( A_1 + \cdots + A_g + A_{g+1} = 0 \).

This is because an \( x \)-integral enclosing \( x^{i \pm} \) using \( x = x^i \) root of \( P(x) \) as an integration variable is the same as \( \lambda \)-integral \( \int_A d\lambda \) enclosing \( \pm 2\sqrt{Q} \) with \( x = x^i \) in the integrand. Therefore it is straightforward to see that \( X^i = X^i \) for \( i = 1, \ldots, n \).

Let’s denote canonical coordinates of \( M_{A_g} \) by \( \{ u^1, \ldots, u^n \} \). Let \( \{ q^1, \ldots, q^n \} \in \mathbb{C} \) be the set of critical points of \( \lambda(x;t), \lambda'(q_i;t) = 0, \lambda(q_i;t) = u^i(t) \). For notational convenience we will define \( q_{n+1} := q_0 \) and \( u^{n+1} := u^n \).

Consider an integral in \( \lambda \)-plane starting from \( u^i \), crossing the cut \( [-2\sqrt{Q}, +2\sqrt{Q}] \) and going back to \( u^i \), which can be deformed to \( \int_{-2\sqrt{Q}}^{2\sqrt{Q}} - \int_{-2\sqrt{Q}}^{2\sqrt{Q}} = 2\int_{-2\sqrt{Q}}^{2\sqrt{Q}} \). Changing to the \( x \)-variable, this path is the path joining \( (x,y) = (q_i, -\sqrt{(u^i(t))^2 - 4Q}) \) in the bottom sheet to \( (x,y) = (q_i, +\sqrt{(u^i(t))^2 - 4Q}) \) in the top sheet via \( (x,y) = (x^{i-}, -2\sqrt{Q}) \) which we will denote by \( C_i, i = 1, \ldots, n + 1 \). Therefore we have that

\[
\tilde{Y}_i(t,Q) = \int_{B_i} dS_{SW} = \int_{C_i} dS_{SW} - \int_{C_{n+1}} dS_{SW} + R_i(t,Q)
\]

\[
= 2\int_{-2\sqrt{Q}}^{2\sqrt{Q}} \frac{x^i(t_1 - \lambda, t_2, \ldots, t_n) d\lambda}{\sqrt{\lambda^2 - 4Q}} - 2\int_{-2\sqrt{Q}}^{2\sqrt{Q}} \frac{x^{i+1}(t_1 - \lambda, t_2, \ldots, t_n) d\lambda}{\sqrt{\lambda^2 - 4Q}} + R_i(t,Q)
\]

where \( R_i(t,Q) = \int_{B_i \setminus (C_i, C_{n+1})} dS_{SW} \) is a function analytic at \( Q = 0 \). The first two integrals have been discussed in the proof of Proposition 4.4.2. The gradient \( (p_{\tilde{Y}_i}, q_{\tilde{Y}_i}) \) of \( \tilde{Y}_i \) can be seen to take the form (4.16). For example, the leading term of \( p_{\tilde{Y}_i} \) is

\[
(\xi'(t) - \xi^{i+1}(t)) \log Q = (\xi'(t) + \sum_{k=1}^n \xi^k(t)) \log Q = g_{ij} \xi^j(t) \log Q = \xi_i(t) \log Q,
\]

where we have used \( g_{ij} = \delta_{ij} + 1, \xi'(t) := dx^i(t) \) and \( x^1 + \cdots + x^{n+1} = 0 \) which implies \( \xi^1 + \cdots + \xi^{n+1} = 0 \).

We arrive at the same situation we were at the end of the proof of Proposition 4.4.2 and the remaining of the arguments will be identical. We conclude that \( \{ \tilde{X}, \tilde{Y} \} \) forms a system of canonical coordinates on the coordinates cross of \( M_{A_g} \otimes \mathbb{P}^1 \). Dropping tildes, the proposition is proven.

Let \( S_{A_g} = S_{A_g}(\{ X^i \}, Q) \) be the generating function for the Lagrangian submanifold \( L_a \subset M_{A_g} \otimes \mathbb{P}^1 \). We have that

\[
b_i = Y_i = \frac{\partial S_{A_g}(\{ X^k \}, Q)}{\partial X^i} = 2\pi i \frac{\partial S_{A_g}(\{ X^k \}, Q)}{\partial a^i}.
\]

Therefore, the Seiberg-Witten prepotential is given by \( S_{SW}(\{ a^i \}, \Lambda) = 2\pi i S_{A_g}(\{ a^i \}, \Lambda^{2g+2}) \).

## 4.5 \( \nu \)-Periods of \( M = M' \otimes M'' \) as Period Integrals

In the previous section, it is unclear why odd periods on the coordinate cross of \( M \otimes \mathbb{P}^1 \) are given by period integrals. In particular, why should \( A \) and \( B \)-periods of the Seiberg-Witten differential on Seiberg-Witten curves be related to \( M_{A_g} \otimes \mathbb{P}^1 \)? In this section we generalize Proposition 4.4.1 to obtain a \( \nu \)-period on the
coordinates cross of $M = M' \otimes M''$ for any two arbitrary Frobenius manifolds $M'$ and $M''$ as a period integral on some Riemann surface. This shows that there is nothing specific about the tensor product with $QH^*(\mathbb{P}^1)$ and that period integrals naturally arise in products of Frobenius manifolds.

Suppose that flat coordinates of $M'$ are given by $t = (t^1, t^2, ..., t^n)$ then let us define $\vec{t} := (0, t^2, ..., t^n)$. We claim the following

**Theorem 4.5.1** Let $M'$ and $M''$ be $n'$ and $n''$-dimensional Frobenius manifolds respectively. Suppose that $\xi' = \xi'(t'; \nu'; \lambda) := \text{d}x'(t'; \nu'; \lambda)$ is a gradient of a $(\nu'; \lambda)$-period $x'(t'; \nu'; \lambda)$ of $M'$ and $\xi'' = \xi''(t''; \nu''; \lambda) := \text{d}x''(t''; \nu''; \lambda)$ is a gradient of $(\nu', \lambda)$-period $x''(t''; \nu''; \lambda)$ of $M''$ then

$$
\psi(t', t''; \nu) = \oint_C \xi'(\vec{t}'; \nu'; -\lambda) \otimes \xi''(t''; \nu''; +\lambda) d\lambda
$$

is a gradient of $\nu$-period on coordinates cross of $M = M' \otimes M''$ where $\nu = \nu' + \nu'' + 1/2$ and $C$ is an arbitrary closed contour on a Riemann surface where the integrand is well-defined.

Of course, we can write the equation in the coordinates form $\psi = \psi_{\alpha'\alpha''} \text{d}t^\alpha' \otimes \text{d}t^\alpha''$ on the coordinates cross as

$$
\psi_{\alpha'\alpha''}(t', t''; \nu) = \oint_C \xi'_{\alpha'}(\vec{t}'; \nu'; -\lambda) \xi''_{\alpha''}(t''; \nu''; +\lambda) d\lambda
$$

Let $\vec{t}' := \vec{t}'(\vec{t}; \nu'; -\lambda)$ and $\xi''(t''; \nu''; +\lambda)$ as before, then (4.20) can be written more compactly as $\psi = \oint_C \xi' \otimes \xi'' d\lambda$. The integral (4.20) can be performed on any closed contour $C$ on a surface where $\xi' \otimes \xi''$ is defined as a function of $\lambda$. There is no guarantee that a closed contour will exist for any $\nu', \nu'' \in \mathbb{C}$, but it is possible in the simple case $\nu', \nu'' \in \mathbb{Q}$ as we shall see in the following. Let $\{u^{n_1}, ..., u^{n_m}\}$ be the canonical coordinates of $M'$ and define the rays $L'_1, ..., L'_n$ by:

$$
L'_i := \{-u^i + \rho e^{i\phi} \mid \rho \in \mathbb{R}_+\}.
$$

then $\vec{t}'$ is a well-defined function for $\lambda \in \mathbb{C} \setminus \bigcup_{i=1}^{n'} L'_i$ (see [10, Section 4]). Similarly, let $\{u^{n_{m_1}}, ..., u^{n_{m_m}}\}$ be the canonical coordinates of $M''$ and define the rays $L''_{n_{m_1}}, ..., L''_{n_{m_m}}$ by:

$$
L''_{n_i} := \{+u^{n_i} + \rho e^{i\phi} \mid \rho \in \mathbb{R}_+\}.
$$

then $\xi''$ is well-defined for $\lambda \in \mathbb{C} \setminus \bigcup_{i=1}^{n_m} L''_{n_i}$. Assuming we are working on a dense subset such that $\{-u^{n_1}, ..., u^{n_n}, u^{n_{m_1}}, ..., u^{n_{m_m}}\}$ are pairwise distinct, then it is possible to pick $\phi \in [0, 2\pi)$ such that $\{L'_1, ..., L'_n\}$ and $\{L''_{n_{m_1}}, ..., L''_{n_{m_m}}\}$ intersect trivially pairwise. Let us fix a pair $(i', i'')$ for some $i' = 1, ..., n'$ and $i'' = 1, ..., n''$, then we can choose $\vec{t}'$ and $\vec{t}''$ such that their monodromies around $\lambda = u^{n_i}$ and $\lambda = u^{n_{m_i}}$ are multiplication by $e^{\pi i(\nu'+1/2)}$ and $e^{\pi i(\nu''+1/2)}$ respectively [10, Lemma 4.5]. Let $m \in \mathbb{Z}$ be such that $m(\nu'+1/2) + m(\nu''+1/2) \in \mathbb{Z}$. Then it is possible to glue $m$ copies of $\mathbb{C} \setminus \bigcup_{i=1}^{n'} L'_i \cup \bigcup_{i=1}^{n_{m}} L''_{n_i}$ appropriately along the cuts $L'_i$ and $L''_{n_i}$ to yield a non-compact Riemann surface $\Lambda_{\nu'}$ such that the path $C$ enclosing $u^{n_i}$ and $u^{n_{m_i}}$, $m$ times, will form a closed contour on $\Lambda_{\nu'}$. We have that $\xi' \otimes \xi''$ is well-defined on some open subset of $\Lambda_{\nu'}$ containing $C$ as needed.

**Remark 4.5.2** We note that the definition of $\Lambda_{\nu'}$ varies with the point on the coordinate cross, in other words, it is parameterized by the coordinates cross. Therefore, we naturally obtain a family of Riemann surfaces by studying the $\nu$-periods of $M = M' \otimes M''$.

Let us now prove Theorem 4.5.1

**Proof**: On $M = M' \otimes M''$, the $\nu$-period equation is

$$
\partial_{t^\alpha'} \psi \cdot \mathcal{U} = \psi \left( \mu + \nu - \frac{1}{2} \right) C_{\alpha' \alpha''}.
$$

Since we are dealing with the formula on the coordinates cross, we only need to verify the equation

$$
\partial_{t^{\alpha'}} \psi \cdot (\mathcal{U} \otimes 1^n + 1^n \otimes \mathcal{U}'' - t^{1^n} 1' \otimes 1^n) = \psi \left( \mu' + 1^n + 1' \otimes \mu'' + \nu - \frac{1}{2} \right) C_{\alpha' \alpha''} \otimes C_{\alpha''}.
$$

for $\alpha' \alpha'' = \alpha' \beta''$ and $\alpha' \alpha'' = 1' \alpha''$. Here we have used (4.7), (4.6) and (4.5) for the expression of $\mathcal{U}, C_{\alpha' \alpha''}$ and $\mu$ on coordinates cross. We recall that on coordinate cross $t^{1^n} \alpha'' = t^{1^n} t^{1' \alpha''} = t^{1' \alpha''}$ and $t^{1' \alpha''} = 0$, $\forall \alpha', \alpha'' > 1$, in particular $t^1 = t^{1' 1'} = t^{1' \alpha' \alpha''}$. Both $\mathcal{U} \otimes 1^n$ and $1' \otimes \mathcal{U}''$ contains the term $t^{1' 1' \otimes 1''} = t^{1' \alpha' \alpha''}$. We have
two equivalent choices, either $t_1^{1'}t_1' \otimes 1^n$ will cancel a term in $\mathcal{U}' \otimes 1^n$ or $1' \otimes \mathcal{U}''$, here we will go with the first choice. Now, we add and subtract $\lambda' \otimes 1^n$ in $\mathcal{U}$, this gives us

$$\mathcal{U} = \mathcal{U}'(\lambda) \otimes 1^n + 1' \otimes (\mathcal{U}'' - \lambda)$$

where $\mathcal{U}'(\lambda)$ is a multiplication by the Euler vector field $E'$ of $M'$ with $\lambda$ replacing $t_1'$. In proving (4.20) we shall use the following fact that $\tilde{\xi} = \xi(\tilde{t}; \nu; -\lambda)$ and $\xi'' = \xi''(t'; \nu'\nu''; +\lambda)$ satisfy

$$\partial_\alpha \tilde{\xi} \cdot \mathcal{U}'(\lambda) = \tilde{\xi} \left( \mu' + \nu' - \frac{1}{2} \right), \quad \partial_\alpha \tilde{\xi} \cdot \mathcal{U}''(\lambda) = \tilde{\xi} \left( \mu' + \nu' - \frac{1}{2} \right) C''_{\alpha''}, \quad \alpha = 2, \ldots, n'. $$

$$\partial_\alpha \xi''(\mathcal{U}'' - \lambda) = \xi'' \left( \mu'' + \nu'' - \frac{1}{2} \right) C''_{\alpha''}, \quad \alpha = 1, \ldots, n''.$$ 

Also, recall from the proof of [10] Lemma 3.6] that $\partial_\alpha \tilde{\xi} = \partial_\alpha \tilde{\xi} \cdot C'_{\alpha}$, and $\partial_\alpha \xi'' = \partial_\alpha \xi'' \cdot C'_{\alpha} = -\partial_\alpha \xi'' \cdot C'_{\alpha'}$. For $\alpha' = \alpha' \nu', \alpha = 2, \ldots, n'$ we have

$$\partial_\alpha \nu' \psi \cdot U = \int (\partial_\alpha \tilde{\xi} \otimes \xi'') \cdot U d\lambda = \int (\partial_\alpha \tilde{\xi} \otimes \xi'') \cdot \left( (\mathcal{U}'(\lambda) \otimes 1^n + 1' \otimes (\mathcal{U}'' - \lambda)) \right) d\lambda$$

Similarly, we have for $\alpha' = 1' \nu'', \alpha'' = 1, \ldots, n''$

$$\partial_\alpha \nu'' \psi \cdot U = \int (\tilde{\xi} \otimes \partial_\alpha \nu'' \xi'') \cdot U d\lambda = \int (\tilde{\xi} \otimes \partial_\alpha \nu'' \xi'') \cdot \left( (\mathcal{U}'(\lambda) \otimes 1^n + 1' \otimes (\mathcal{U}'' - \lambda)) \right) d\lambda$$

Therefore the theorem is proven.

**Corollary 4.5.3** Let $M'$ and $M''$ be Frobenius manifolds. Suppose that $x' = x'(t'; \nu; \lambda)$ and $x'' = x''(t'; \nu'; \lambda)$ are $(\nu', \lambda)$ and $(\nu'', \lambda)$-periods of $M'$ and $M''$ respectively. Then

$$\omega(1', t'; \nu) = \int (\partial_\lambda x(\tilde{t}; \nu; -\lambda)) x''(t'; \nu' \nu''; +\lambda) d\lambda$$

is a $\nu$-period $\omega = \omega(1', t''; \nu)$ on the coordinates cross of $M = M' \otimes M''$.

**Proof:** Since we are on the coordinates cross, we only need to check that $\psi_{1' \nu'} = \partial \omega / \partial t''^{1'}$, $\psi_{1' \nu''} = \partial \omega / \partial t'^{1'}$. This can easily seen to be true.

We can recover the solution of odd period on $M = M_{A_n} \otimes \mathbb{Q}H^*(\mathbb{P}^1)$ as given in Proposition 4.4.1 as a special...
case of Corollary 4.5.3 Let the flat coordinates of $QH^*(\mathbb{P}^1)$ be given by \{t, s\}. Then it is not hard to show that the $(0, \lambda)$-period is given by

$$x(t, s; \lambda) = \tan^{-1}\left(\frac{t - \lambda}{\sqrt{4Q - (t - \lambda)^2}}\right), \quad y(t, s; \lambda) = s,$$

where $Q := e^s$.

Therefore,

$$\partial_{\lambda} x(0, s; -\lambda) = \frac{1}{\sqrt{\lambda^2 - 4Q}}, \quad \partial_{\lambda} y(0, s; -\lambda) = 0.$$

The Frobenius manifold $M_{A_n}$ is defined by $\lambda(x; t) = x^{n+1} + y^n x^{n-1} + ... + y^1$ with flat coordinates given by \{t^\alpha\} (see Section 4.2.3). The flat coordinates of the intersection form of $M_{A_n}$ is given by \{x^1, ..., x^n\} where $x^i = x^i(t)$ is the $i$-th root of $P(x) = 0$. Similarly the $(0, \lambda)$-period for $M_{A_n}$ are given by $x^i(t; \lambda) = x^i(t^1 - \lambda, t^2, ..., t^n)$ or the $i$-th root of $\lambda(x; t) = \lambda$.

Applying Corollary 4.5.3 with $x' = x, x'' = x^i$ yields an odd period on $M = M_{A_n} \otimes QH^*(\mathbb{P}^1)$:

$$\omega(t, Q) = \oint \frac{x^i(t^1 - \lambda, t^2, ..., t^n)}{\sqrt{\lambda^2 - 4Q}} d\lambda.$$

As we have seen, we can rewrite the integrand as the Seiberg-Witten differential $dS_{SW}$ and so $\omega(t, Q)$ is given by a period integral on a Seiberg-Witten curve, varying over the family of Seiberg-Witten curves.

**Remark 4.5.4** If we have chosen instead $x' = y, x'' = x^i$ then we get $\omega(t, Q) = 0$ which is trivially a solution to the odd period equation.
Bibliography


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