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Torsion, TQFT, and Seiberg–Witten invariants of 3–manifolds

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Abstract

We prove a conjecture of Hutchings and Lee relating the Seiberg–Witten invariants of a closed 3–manifold X with $b_1 \geq 1$ to an invariant that "counts" gradient flow lines—including closed orbits—of a circle-valued Morse function on the manifold. The proof is based on a method described by Donaldson for computing the Seiberg–Witten invariants of 3–manifolds by making use of a "topological quantum field theory," which makes the calculation completely explicit. We also realize a version of the Seiberg–Witten invariant of X as the intersection number of a pair of totally real submanifolds of a product of vortex moduli spaces on a Riemann surface constructed from geometric data on X. The analogy with recent work of Ozsváth and Szabó suggests a generalization of a conjecture of Salamon, who has proposed a model for the Seiberg–Witten–Floer homology of X in the case that X is a mapping torus.

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1 Introduction

In [5] and [6], Hutchings and Lee investigate circle-valued Morse theory for Riemannian manifolds X with first Betti number $b_1 \geq 1$. Given a generic Morse function $\phi\colon X \to S^1$ representing an element of infinite order in $H^1(X;\mathbb{Z})$ and having no extrema, they determine a relationship between the Reidemeister torsion $\tau(X,\phi)$ associated to ϕ, which is in general an element of the field $\mathbb{Q}(t)$, and the torsion of a "Morse complex" M^* defined over the ring $L_{\mathbb{Z}}$ of integer-coefficient Laurent series in a single variable t. If S is the inverse image of a regular value of ϕ then upward gradient flow of ϕ induces a return map $F\colon S \to S$ that is defined away from the descending manifolds of the critical points of ϕ. The two torsions $\tau(X,\phi)$ and $\tau(M^*)$ then differ by multiplication by the zeta function $\zeta(F)$. In the case that X has dimension three, which will be our exclusive concern in this paper, the statement reads

$$\tau(M^*)\zeta(F) = \tau(X,\phi), \tag{1}$$

up to multiplication by $\pm t^k$. One should think of the left-hand side as "counting" gradient flows of ϕ; $\tau(M^*)$ is concerned with gradient flows between critical points of ϕ, while $\zeta(F)$, defined in terms of fixed points of the return map, describes the closed orbits of ϕ. It should be remarked that $\tau(X,\phi) \in \mathbb{Q}(t)$ is in fact a polynomial if $b_1(X) > 1$, and "nearly" so if $b_1(X) = 1$; see [10] or [17] for details.

If the three–manifold X is zero-surgery on a knot $K \subset S^3$ and ϕ represents a generator in $H^1(X;\mathbb{Z})$, the Reidemeister torsion $\tau(X,\phi)$ is essentially (up to a standard factor) the Alexander polynomial Δ_K of the knot. It has been proved by Fintushel and Stern [4] that the Seiberg–Witten invariant of $X \times S^1$, which can be identified with the Seiberg–Witten invariant of X, is also given by the Alexander polynomial (up to the same standard factor). More generally, Meng and Taubes [10] show that the Seiberg–Witten invariant of any closed three–manifold with $b_1(X) \geq 1$ can be identified with the Milnor torsion $\tau(X)$ (after summing over the action of the torsion subgroup of $H^2(X;\mathbb{Z})$), from which it follows that if $\mathcal{S}$ denotes the collection of spin^c structures on X,

$$\sum_{\alpha\in\mathcal{S}} SW(\alpha)t^{c_1(\alpha)\cdot S/2} = \tau(X,\phi), \tag{2}$$

up to multiplication by $\pm t^k$ (in [10] the sign is specified). Here $c_1(\alpha)$ denotes the first Chern class of the complex line bundle $\det\alpha$ associated to α.

These results point to the natural conjecture, made in [6], that the left-hand side of (1) is equal to the Seiberg–Witten invariant of X—or more precisely to a combination of invariants as in (2)—independently of the results of Meng and Taubes. We remark that the theorem of Meng and Taubes announced in [10] depends on surgery formulae for Seiberg–Witten invariants, and a complete proof of these results has not yet appeared in the literature. The conjecture of Hutchings and Lee gives a direct interpretation of the Seiberg–Witten invariants in terms of geometric information, reminiscent of Taubes's work relating Seiberg–Witten invariants and holomorphic curves on symplectic 4–manifolds. The proof of this conjecture is the aim of this paper; combined with the work in [6] and [5] it establishes an alternate proof of the Meng–Taubes result (for closed manifolds) that does not depend on the surgery formulae for Seiberg–Witten invariants used in [10] and [4].

Remark 1.1 In fact, the conjecture in [6] is more general, as follows: Hutchings and Lee define an invariant $I\colon \mathcal{S} \to \mathbb{Z}$ of spin^c structures based on the counting of gradient flows, which is conjectured to agree with the Seiberg–Witten invariant. The proof presented in this paper gives only an "averaged" version of this statement, ie, that the left hand side of (1) is equal to the left hand side of (2). It can be seen from the results of [6] that this averaged statement is in fact enough to recover the full Meng–Taubes theorem: see in particular [6], Lemma 4.5. It may also be possible to extend the methods of this paper to distinguish the Seiberg–Witten invariants of spin^c structures whose determinant lines differ by a non-torsion element $a \in H^2(X;\mathbb{Z})$ with $a \cdot S = 0$.

We also show that the "averaged" Seiberg–Witten invariant is equal to the intersection number of a pair of totally real submanifolds in a product of symmetric powers of a slice for ϕ. This is a situation strongly analogous to that considered by Ozsváth and Szabó in [14] and [15], and one might hope to define a Floer-type homology theory along the lines of that work. Such a construction would suggest a generalization of a conjecture of Salamon, namely that the Seiberg–Witten–Floer homology of X agrees with this new homology (which is a "classical" Floer homology in the case that X is a mapping torus—see [16]).

2 Statement of results

Before stating our main theorems, we need to recall a few definitions and introduce some notation. First is the notion of the torsion of an acyclic chain complex; basic references for this material include [11] and [17].

2.1 Torsion

By a *volume* ω for a vector space W of dimension n we mean a choice of nonzero element $\omega \in \Lambda^n W$. Let $0 \to V' \to V \to V'' \to 0$ be an exact sequence of finite-dimensional vector spaces over a field k. For volumes ω' on V' and ω'' on V'', the induced volume on V will be written $\omega'\omega''$; if ω_1, ω_2 are two volume elements for V, then we can write $\omega_1 = c\omega_2$ for some nonzero element $c \in k$ and by way of shorthand, write $c = \omega_1/\omega_2$. More generally, let $\{C_i\}_{i=0}^n$ be a complex of vector spaces with differential $\partial\colon C_i \to C_{i-1}$, and let us assume that C_* is acyclic, ie, $H_*(C_*) = 0$. Suppose that each C_i comes equipped with a volume element ω_i, and choose volumes ν_i arbitrarily on each image ∂C_i, $i = 2, \ldots, n-1$. From the exact sequence

$$0 \to C_n \to C_{n-1} \to \partial C_{n-1} \to 0$$

define $\tau_{n-1} = \omega_n \nu_{n-1}/\omega_{n-1}$. For $i = 2, \ldots, n-2$ use the exact sequence

$$0 \to \partial C_{i+1} \to C_i \to \partial C_i \to 0$$

to define $\tau_i = \nu_{i+1}\nu_i/\omega_i$. Finally, from

$$0 \to \partial C_2 \to C_1 \to C_0 \to 0$$

define $\tau_1 = \nu_2\omega_0/\omega_1$. We then define the *torsion* $\tau(C_*, \{\omega_i\}) \in k \setminus \{0\}$ of the (volumed) complex C_* to be:

$$\tau(C_*) = \prod_{i=1}^{n-1} \tau_i^{(-1)^{i+1}} \tag{3}$$

It can be seen that this definition does not depend on the choice of ν_i. Note that in the case that our complex consists of just two vector spaces,

$$C_* = 0 \to C_i \xrightarrow{\partial} C_{i-1} \to 0,$$

we have that $\tau(C) = \det(\partial)^{(-1)^i}$. We extend the definition of $\tau(C_*)$ to non-acyclic complexes by setting $\tau(C_*) = 0$ in this case.

As a slight generalization, we can allow the chain groups C_i to be finitely generated free modules over an integral domain K with fixed ordered bases rather than vector spaces with fixed volume elements, as follows. Write $Q(K)$ for the field of fractions of K, then form the complex of vector spaces $Q(K) \otimes_K C_i$. The bases for the C_i naturally give rise to bases, and hence volumes, for $Q(K) \otimes_K C_i$. We understand the torsion of the complex of K–modules C_i to be the torsion of this latter complex, and it is therefore a nonzero element of the field $Q(K)$.

Let X be a connected, compact, oriented smooth manifold with a given CW decomposition. Following [17], suppose $\varphi\colon \mathbb{Z}[H_1(X;\mathbb{Z})] \to K$ is a ring homomorphism into an integral domain K. The universial abelian cover $\tilde{X}$ has a natural CW decomposition lifting the given one on X, and the action of the deck transformation group $H_1(X;\mathbb{Z})$ naturally gives the cell chain complex $C_*(\tilde{X})$ the structure of a $\mathbb{Z}[H_1(X;\mathbb{Z})]$–module. As such, $C_i(\tilde{X})$ is free of rank equal to the number of i–cells of X. We can then form the twisted complex $C_*^{\varphi}(\tilde{X}) = K \otimes_{\varphi} C_*(\tilde{X})$ of K–modules. We choose a sequence e of cells of $\tilde{X}$ such that over each cell of X there is exactly one element of e, called a *base sequence*; this gives a basis of $C_*^{\varphi}(\tilde{X})$ over K and allows us to form the torsion $\tau_{\varphi}(X,e) \in Q(K)$ relative to this basis. Note that the torsion $\tau_{\varphi}(X,e')$ arising from a different choice e' of base sequence stands in the relationship $\tau_{\varphi}(X,e) = \pm\varphi(h)\tau_{\varphi}(X,e')$ for some $h \in H_1(X;\mathbb{Z})$ (here, as is standard practice, we write the group operation in $H_1(X;\mathbb{Z})$ multiplicatively when dealing with elements of $\mathbb{Z}[H_1(X;\mathbb{Z})]$). The set of all torsions arising from all such choices of e is "the" torsion of X associated to φ and is denoted $\tau_{\varphi}(X)$.

We are now in a position to define the torsions we will need.

Definition 2.1 (1) For X a smooth manifold as above with $b_1(X) \geq 1$, let $\phi\colon X \to S^1$ be a map representing an element $[\phi]$ of infinite order in $H^1(X;\mathbb{Z})$. Let C be the infinite cyclic group generated by the formal variable t, and let $\varphi_1 : \mathbb{Z}[H_1(X;\mathbb{Z})] \to \mathbb{Z}[C]$ be the map induced by the homomorphism $H_1(X;\mathbb{Z}) \to C$, $a \mapsto t^{\langle[\phi],a\rangle}$. Then the *Reidemeister torsion* $\tau(X,\phi)$ of X associated to ϕ is defined to be the torsion $\tau_{\varphi_1}(X)$.

(2) Write H for the quotient of $H_1(X;\mathbb{Z})$ by its torsion subgroup, and let $\varphi_2 : \mathbb{Z}[H_1(X;\mathbb{Z})] \to \mathbb{Z}[H]$ be the map induced by the projection $H_1(X;\mathbb{Z}) \to H$. The *Milnor torsion* $\tau(X)$ is defined to be $\tau_{\varphi_2}(X)$.

Remark 2.2 (1) Some authors use the term *Reidemeister torsion* to refer to the torsion $\tau_{\varphi}(X)$ for arbitrary φ; and other terms, eg, Reidemeister–Franz–DeRham torsion, are also in use.

(2) The torsions in Definition 2.1 are defined for manifolds X of arbitrary dimension, with or without boundary. We will be concerned only with the case that X is a closed manifold of dimension 3 with $b_1(X) \geq 1$. In the case $b_1(X) > 1$, work of Turaev [17] shows that $\tau(X)$ and $\tau(X,\phi)$, naturally subsets of $\mathbb{Q}(H)$ and $\mathbb{Q}(t)$, are actually subsets of $\mathbb{Z}[H]$ and $\mathbb{Z}[t,t^{-1}]$. Furthermore, if $b_1(X) = 1$ and $[\phi] \in H^1(X;\mathbb{Z})$ is a generator, then $\tau(X) = \tau(X,\phi)$ and $(t-1)^2\tau(X) \in \mathbb{Z}[t,t^{-1}]$. Rather than thinking of torsion as a set of elements in a field we normally identify it with a representative "defined up to multiplication

by $\pm t^k$" or similar, since by the description above any two representatives of the torsion differ by some element of the group (C or H) under consideration.

2.2 S^1–Valued Morse Theory

We review the results of Hutchings and Lee that motivate our theorems. As in the introduction, let X be a smooth closed oriented 3–manifold having $b_1(X) \geq 1$ and let $\phi\colon X \to S^1$ be a smooth Morse function. We assume (1) ϕ represents an indivisible element of infinite order in $H^1(X,\mathbb{Z})$; (2) ϕ has no critical points of index 0 or 3; and (3) the gradient flow of ϕ with respect to a Riemannian metric on X is Morse–Smale. Such functions always exist given our assumptions on X.

Given such a Morse function ϕ, fix a smooth level set S for ϕ. Upward gradient flow defines a return map $F\colon S \to S$ away from the descending manifolds of the critical points of ϕ. The *zeta function* of F is defined by the series

$$\zeta(F) = \exp\left(\sum_{k\geq 1} \mathrm{Fix}(F^k)\frac{t^k}{k}\right)$$

where $\mathrm{Fix}(F^k)$ denotes the number of fixed points (counted with sign in the usual way) of the k-th iterate of F. One should think of $\zeta(F)$ as keeping track of the number of closed orbits of ϕ as well as the "degree" of those orbits. For future reference we note that if $h\colon S \to S$ is a diffeomorphism of a surface S then

$$\zeta(h) = \sum_k L(h^{(k)})t^k \tag{4}$$

where $L(h^{(k)})$ is the Lefschetz number of the induced map on the k-th symmetric power of S (see [16], [7]).

We now introduce a Morse complex that can be used to keep track of gradient flow lines between critical points of ϕ. Write $L_{\mathbb{Z}}$ for the ring of Laurent series in the variable t, and let M^i denote the free $L_{\mathbb{Z}}$–module generated by the index-i critical points of ϕ. The differential $d_M\colon M^i \to M^{i+1}$ is defined to be

$$d_M x_\mu = \sum_\nu a_{\mu\nu}(t) y_\nu \tag{5}$$

where x_μ is an index-i critical point, $\{y_\nu\}$ is the set of index-$(i+1)$ critical points, and $a_{\mu\nu}(t)$ is a series in t whose coefficient of t^n is defined to be the number of gradient flow lines of ϕ connecting x_μ with y_ν that cross S n

times. Here we count the gradient flows with sign determined by orientations on the ascending and descending manifolds of the critical points; see [6] for more details.

Theorem 2.3 (Hutchings–Lee) *In this situation, the relation (1) holds up to multiplication by* $\pm t^k$.

2.3 Results

The main result of this work is that the left hand side of (1) is equal to the left hand side of (2), without using the results of [10]. Hence the current work, together with that of Hutchings and Lee, gives an alternative proof of the theorem of Meng and Taubes in [10].

Our proof of this fact is based on ideas of Donaldson for computing the Seiberg–Witten invariants of 3–manifolds. We outline Donaldson's construction here; see Section 4 below for more details. Given $\phi\colon X \to S^1$ a generic Morse function as above and S the inverse image of a regular value, let $W = X \setminus nbd(S)$ be the complement of a small neighborhood of S. Then W is a cobordism between two copies of S (since we assumed ϕ has no extrema—note we may also assume S is connected). Note that two spin^c structures on X that differ by an element $a \in H^2(X;\mathbb{Z})$ with $a([S]) = 0$ restrict to the same spin^c structure on W, in particular, spin^c structures σ on W are determined by their degree $m = \langle c_1(\sigma), S\rangle$. Note that the degree of a spin^c structure is always even.

Now, a solution of the Seiberg–Witten equations on W restricts to a solution of the *vortex equations* on S at each end of W (more accurately, we should complete W by adding infinite tubes $S\times(-\infty,0]$, $S\times[0,\infty)$ to each end, and consider the limit of a finite-energy solution on this completed space)—see [3], [13] for example. These equations have been extensively studied, and it is known that the moduli space of solutions to the vortex equations on S can be identified with a symmetric power $\mathrm{Sym}^n S$ of S itself: see [1], [8]. Donaldson uses the restriction maps on the Seiberg–Witten moduli space of W to obtain a self-map κ_n of the cohomology of $\mathrm{Sym}^n S$, where n is defined by $n = g(S) - 1 - \frac{1}{2}|m|$ if $b_1(X) > 1$ and $n = g(S) - 1 + \frac{1}{2}m$ if $b_1(X) = 1$ (here $g(S)$ is the genus of the orientable surface S). The alternating trace $\mathrm{Tr}\,\kappa_n$ is identified as the sum of Seiberg–Witten invariants of spin^c structures on X that restrict to the given spin^c structure on W—that is, the coefficient of t^n on the left hand side of (2). For a precise statement, see Theorem 4.1.

Our main result is the following.

Theorem 2.4 *Let X be a Riemannian 3–manifold with $b_1(X) \geq 1$, and fix an integer $n \geq 0$ as above. Then we have*

$$\operatorname{Tr}\kappa_n = [\tau(M^*)\,\zeta(F)]_n, \tag{6}$$

where $\tau(M^*)$ is represented by $t^N \det(d_M)$, and N is the number of index 1 critical points of ϕ. Here Tr denotes the alternating trace and $[\,\cdot\,]_n$ denotes the coefficient of t^n of the polynomial enclosed in brackets.

This fact immediately implies the conjecture of Hutchings and Lee. Furthermore, we will make the following observation:

Theorem 2.5 *There is a smooth connected representative S for the Poincaré dual of $[\phi] \in H^1(X;\mathbb{Z})$ such that $\operatorname{Tr}\kappa_n$ is given by the intersection number of a pair of totally real embedded submanifolds in $\mathrm{Sym}^{n+N}S \times \mathrm{Sym}^{n+N}S$.*

This may be the first step in defining a Lagrangian-type Floer homology theory parallel to that of Ozsváth and Szabó, one whose Euler characteristic is *a priori* a combination of Seiberg–Witten invariants. In the case that X is a mapping torus, a program along these lines has been initiated by Salamon [16]. In this case the two totally real submanifolds in Theorem 2.5 reduce to the diagonal and the graph of a symplectomorphism of $\mathrm{Sym}^n S$ determined by the monodromy of the mapping torus, both of which are in fact Lagrangian.

The remainder of the paper is organized as follows: Section 3 gives a brief overview of some elements of Seiberg–Witten theory and the dimensional reduction we will make use of, and Section 4 gives a few more details on this reduction and describes the TQFT we use to compute Seiberg–Witten invariants. Section 5 proves a theorem that gives a means of calculating as though a general cobordism coming from an S^1–valued Morse function of the kind we are considering posessed a naturally-defined monodromy map; Section 6 collects a few other technical results of a calculational nature, the proof of one of which is the content of Section 9. In Section 7 we prove Theorem 2.4 by a calculation that is fairly involved but is not essentially difficult, thanks to the tools provided by the TQFT. Section 8 proves Theorem 2.5.

3 Review of Seiberg–Witten theory

We begin with an outline of some aspects of Seiberg–Witten theory for a 3–manifolds. Recall that a spin^c structure on a 3–manifold X is a lift of the oriented orthogonal frame bundle of X to a principal $\mathrm{spin}^c(3)$–bundle σ. There are two representations of $\mathrm{spin}^c(3) = \mathrm{Spin}(3) \times U(1)/\pm 1 = SU(2) \times U(1)/\pm 1$ that will interest us, namely the spin representation $\mathrm{spin}^c(3) \to SU(2)$ and also the projection $\mathrm{spin}^c(3) \to U(1)$ given by $[g, e^{i\theta}] \mapsto e^{2i\theta}$. For a spin^c structure σ the first of these gives rise to the associated *spinor bundle* W which is a hermitian 2–plane bundle, and the second to the *determinant line bundle* $L \cong \wedge^2 W$. We define $c_1(\sigma) := c_1(L)$. The Levi–Civita connection on X together with a choice of hermitian connection A on $L^{1/2}$ gives rise to a hermitian connection on W that is compatible with the action of Clifford multiplication $c\colon T^*_{\mathbb{C}}X \to \mathrm{End}_0 W = \{\text{traceless endomorphisms of } W\}$, and thence to a Dirac operator $D_A : \Gamma(W) \to \Gamma(W)$.

The *Seiberg–Witten equations* are equations for a pair $(A, \psi) \in \mathcal{A}(L) \times \Gamma(W)$ where $\mathcal{A}(L)$ denotes the space of hermitian connections on $L^{1/2}$, and read:

$$\begin{array}{rcl} D_A\psi & = & 0 \\ c(\star F_A + i \star \mu) & = & \psi \otimes \psi^* - \frac{1}{2}|\psi|^2 \end{array} \tag{7}$$

Here $\mu \in \Omega^2(X)$ is a closed form used as a perturbation; if $b_1(X) > 1$ we may choose μ as small as we like.

On a closed oriented 3–manifold the *Seiberg–Witten moduli space* is the set of $L^{2,2}$ solutions to the above equations modulo the action of the gauge group $\mathcal{G} = L^{2,3}(X; S^1)$, which acts on connections by conjugation and on spinors by complex multiplication. For generic choice of perturbation μ the moduli space $\mathcal{M}_\sigma$ is a compact zero–dimensional manifold that is smoothly cut out by its defining equations (if $b_1(X) > 0$). There is a way to orient $\mathcal{M}_\sigma$ using a so-called homology orientation of X, and the *Seiberg–Witten invariant* of X in the spin^c structure σ is defined to be the signed count of points of $\mathcal{M}_\sigma$. One can show that if $b_1(X) > 1$ then the resulting number is independent of all choices involved and depends only on X (with its orientation); while if $b_1(X) = 1$ there is a slight complication: in this case we need to make a choice of generator o for the free part of $H^1(X; \mathbb{Z})$ and require that $\langle [\mu] \cup o, [X] \rangle > \pi \langle c_1(\sigma) \cup o, [X] \rangle$.

Suppose now that rather than a closed manifold, X is isometric to a product $\Sigma \times \mathbb{R}$ for some Riemann surface Σ. If t is the coordinate in the $\mathbb{R}$ direction, then Clifford multiplication by dt is an automorphism of square -1 of W and therefore splits W into eigen-bundles E and F on which dt acts as multiplication by $-i$ and i, respectively. In fact $F = K^{-1}E$ where K is the canonical bundle of Σ, and $2E - K = L$, the determinant line of σ. Writing a section ψ of W as $(\alpha, \beta) \in \Gamma(E \oplus K^{-1}E)$, we can express the Dirac operator in this decomposition as:

$$D_A\psi = \begin{pmatrix} -i\frac{\partial}{\partial t} & \bar\partial^*_{B,J} \\ \bar\partial_{B,J} & i\frac{\partial}{\partial t} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

Here we have fixed a spin structure (with connection) $K^{1/2}$ on Σ and noted that the choice of a connection A on $L^{1/2} = E - K^{1/2}$ is equivalent to a choice of connection B on E. The metric on $\Sigma \times \mathbb{R}$ induces a complex structure J and area form ω_Σ on Σ. Then $\bar\partial_{B,J}$ is the associated $\bar\partial$ operator on sections of E with adjoint operator $\bar\partial^*_{B,J}$.

The 2–forms $\Omega^2_{\mathbb{C}}(\Sigma\times\mathbb{R})$ split as $\Omega^{1,1}(\Sigma)\oplus[(\Omega^{1,0}(\Sigma)\oplus\Omega^{0,1}(\Sigma))\otimes\Omega^1_{\mathbb{C}}(\mathbb{R})]$, and we will write a form ν as $\Lambda\nu\cdot\omega_\Sigma + \nu^{1,0}dt + \nu^{0,1}dt$ in this splitting. Thus $\Lambda\nu$ is a complex function on $\Sigma\times\mathbb{R}$, while $\nu^{1,0}$ and $\nu^{0,1}$ are 1–forms on Σ. With these conventions, the Seiberg–Witten equations become

$$\begin{aligned} i\dot\alpha &= \bar\partial^*_{B,J}\beta \\ i\dot\beta &= -\bar\partial_{B,J}\alpha \\ 2\Lambda F_B - \Lambda F_K + 2i\Lambda\mu &= i(|\alpha|^2 - |\beta|^2) \\ (2F_B - F_K)^{1,0} + 2i\mu^{1,0} &= \alpha\otimes\bar\beta \end{aligned} \tag{8}$$

One can show that for a finite-energy solution either α or β must identically vanish; apparently this implies any such solution is constant, and the above system of equations descends to Σ when written in temporal gauge (ie, so the connection has no dt component). The above equations (with $\beta = 0$) therefore reduce to the *vortex equations* in E, which are for a pair $(B,\alpha)\in\mathcal{A}(E)\times\Gamma(E)$ and read

$$\bar\partial_{B,J}\alpha = 0 \tag{9}$$

$$i\star F_B + \frac{1}{2}|\alpha|^2 = \tau \tag{10}$$

where τ is a function on Σ satisfying $\int\tau > 2\pi\deg(E)$ and incorporates the curvature F_K and perturbation above. These equations are well-understood, and it is known that the space of solutions to the vortex equations modulo $\mathrm{Map}(\Sigma, S^1)$ is isomorphic to the space of solutions (B,α) of the single equation

$$\bar\partial_{B,J}\alpha = 0$$

modulo the action of $\mathrm{Map}(\Sigma,\mathbb{C}^*)$. The latter is naturally identified with the space of divisors of degree $d = \deg(E)$ on Σ via the zeros of α, and forms a Kähler manifold isomorphic to the d-th symmetric power $\mathrm{Sym}^d\Sigma$, which for brevity we will abbreviate as $\Sigma^{(d)}$ from now on. We write $\mathcal{M}_d(\Sigma,J)$ (or simply $\mathcal{M}(\Sigma)$) for the moduli space of vortices in a bundle E of degree d on Σ.

The situation for $\alpha \equiv 0$ is analogous to the above: in this case β satisfies $\bar{\partial}^*_{B,J}\beta = 0$ so that $\star_2\beta$ is a holomorphic section of $K \otimes E^*$. Replacing β by $\star_2\beta$ shows that the Seiberg–Witten equations reduce to the vortex equations in the bundle $K \otimes E^*$, giving a moduli space isomorphic to $\Sigma^{(2g-2-d)}$.

4 A TQFT for Seiberg–Witten invariants

In this section we describe Donaldson's "topological quantum field theory" for computing the Seiberg–Witten invariants. Suppose W is a cobordism between two Riemann surfaces S_- and S_+. We complete W by adding tubes $S_\pm \times [0,\infty)$ to the boundaries and endow the completed manifold $\hat{W}$ with a Riemannian metric that is a product on the ends. By considering finite-energy solutions to the Seiberg–Witten equations on $\hat{W}$ in some spin^c structure σ, we can produce a Fredholm problem and show that such solutions must approach solutions to the vortex equations on $S_\pm$. Following a solution to its limiting values, we obtain smooth maps between moduli spaces, $\rho_\pm : \mathcal{M}(\hat{W}) \to \mathcal{M}(S_\pm)$. Thus we can form

$$\begin{aligned} \kappa_\sigma = (\rho_- \otimes \rho_+)_*[\mathcal{M}(\hat{W})] &\in H_*(\mathcal{M}(S_-)) \otimes H_*(\mathcal{M}(S_+)) \\ &\cong \hom(H^*(\mathcal{M}(S_-)), H^*(\mathcal{M}(S_+))). \end{aligned}$$

Here we use Poincaré duality and work with rational coefficients.

This is the basis for our "TQFT:" to a surface S we associate the cohomology of the moduli space $\mathcal{M}(S)$, and to a cobordism W between S_- and S_+ we assign the homomorphism κ_σ:

$$\begin{aligned} S &\longmapsto V_S = H^*(\mathcal{M}(S)) \\ W &\longmapsto \kappa_\sigma : V_{S_-} \to V_{S_+} \end{aligned}$$

In the sequel we will be interested only in cobordisms W that satisify the topological assumption $H_1(W, \partial W) = \mathbb{Z}$. Under this asssumption, gluing theory for Seiberg–Witten solutions provides a proof of the central property of TQFTs, namely that if W_1 and W_2 are composable cobordisms then $\kappa_{W_1 \cup W_2} = \kappa_{W_2} \circ \kappa_{W_1}$.

If X is a closed oriented 3–manifold with $b_1(X) > 0$ then the above constructions can be used to calculate the Seiberg–Witten invariants of X, as seen in [2]. We now describe the procedure involved. Begin with a Morse function $\phi\colon X \to S^1$ as in the introduction, and cut X along the level set S to produce a cobordism W between two copies of S, which come with an identification or "gluing map" $\partial_- W \to \partial_+ W$. Write g for the genus of S. The cases $b_1(X) > 1$ and $b_1(X) = 1$ are slightly different and we consider them separately.

Suppose $b_1(X) > 1$, so the perturbation μ in (7) can be taken to be small. Consider the constant solutions to the equations (8) on the ends of $\hat{W}$, or equivalently the possible values of $\rho_\pm$. If $\beta \equiv 0$ then α is a holomorphic section of E and so the existence of a nonvanishing solution requires $\deg(E) \geq 0$. Since μ is small, integrating the third equation in (8) tells us that $2E - K$ is nonpositive. Hence existence of nonvanishing solutions requires $0 \leq \deg(E) \leq \frac{1}{2}\deg(K) = g - 1$. If $\alpha \equiv 0$, then $\star_2\beta$ is a holomorphic section of $K - E$ so to avoid triviality we must have $0 \leq \deg(K) - \deg(E)$, ie, $\deg(E) \leq 2g - 2$. On the other hand, integrating the third Seiberg–Witten equation tells us that $2E - K$ is nonnegative, so that $\deg(E) \geq g - 1$. To summarize we have shown that constant solutions to the Seiberg–Witten equations on the ends of $\hat{W}$ in a spin^c structure σ are just the vortices on S (with the finite-energy hypothesis). If $\det(\sigma) = L$ a necessary condition for the existence of such solutions is $-2g + 2 \leq \deg(L) \leq 2g - 2$ (recall $L = 2E - K$ so in particular L is even). If this condition is satisfied than the moduli space on each end is isomorphic to $\mathcal{M}_n(S) \cong S^{(n)}$ where $n = g - 1 - \frac{1}{2}|\deg(L)|$. Note that by suitable choice of perturbation μ we can eliminate the "reducible" solutions, ie, those with $\alpha \equiv 0 \equiv \beta$, which otherwise may occur at the extremes of our range of values for $\deg(L)$.

Now assume $b_1(X) = 1$. Integrating the third equation in (8) shows

$$\langle c_1(\sigma), S\rangle - \frac{1}{\pi}\langle[\mu], S\rangle = \frac{1}{2\pi}\int_S |\beta|^2 - |\alpha|^2.$$

The left hand side of this is negative by our assumption on μ, and we know that either $\alpha \equiv 0$ or $\beta \equiv 0$. The first of these possibilities gives a contradiction; hence $\beta \equiv 0$ and the system (8) reduces to the vortex equations in E over S. Existence of nontrivial solutions therefore requires $\deg(E) \geq 0$, ie, $\deg(L) \geq 2 - 2g(S)$. Thus the moduli space on each end of $\hat{W}$ is isomorphic to $\mathcal{M}_n(S) \cong S^{(n)}$, where $n = \deg(E) = g - 1 + \frac{1}{2}\deg(L)$ and $\deg(L)$ is any even integer at least $2 - 2g(S)$.

Theorem 4.1 (Donaldson) *Let X, σ, ϕ, S, and W be as above. Write $\langle c_1(\sigma), [S]\rangle = m$ and define either $n = g(S) - 1 - \frac{1}{2}|m|$ or $n = g(S) - 1 + \frac{1}{2}m$ depending whether $b_1(X) > 1$ or $b_1(X) = 1$. Then if $n \geq 0$,*

$$\operatorname{Tr}\kappa_\sigma = \sum_{\tilde{\sigma}\in\mathcal{S}_m} SW(\tilde{\sigma}) \tag{11}$$

where $\mathcal{S}_m$ denotes the set of spin^c *structures $\tilde{\sigma}$ on X such that $\langle c_1(\tilde{\sigma}), [S]\rangle = m$. If $n < 0$ then the right hand side of (11) vanishes. Here* Tr *denotes the graded trace.*

Note that with n as in the theorem, κ_σ is a linear map

$$\kappa_\sigma : H^*(S^{(n)}) \to H^*(S^{(n)});$$

as the trace of κ_σ computes a sum of Seiberg–Witten invariants rather than just $SW(\sigma)$, we use the notation κ_n rather than κ_σ.

Since κ_n obeys the composition law, in order to determine the map corresponding to W we need only determine the map generated by elementary cobordisms, ie, those consisting of a single 1– or 2–handle addition (we need not consider 0– or 3–handles by our assumption on ϕ). In [2], Donaldson uses an elegant algebraic argument to determine these elementary homomorphisms. To state the result, recall that the cohomology of the n-th symmetric power $S^{(n)}$ of a Riemann surface S is given over $\mathbb{Z}$, $\mathbb{Q}$, $\mathbb{R}$, or $\mathbb{C}$ by

$$H^*(S^{(n)}) = \bigoplus_{i=0}^{n} \Lambda^i H^1(S) \otimes \mathrm{Sym}^{n-i}(H^0(S) \oplus H^2(S)). \tag{12}$$

Suppose that W is an elementary cobordism connecting two surfaces Σ_g and Σ_{g+1}. Thus there is a unique critical point (of index 1) of the height function $h\colon W \to \mathbb{R}$, and the ascending manifold of this critical point intersects Σ_{g+1} in an essential simple closed curve that we will denote by c.

Now, c obviously bounds a disk $D \subset W$; the Poincaré–Lefschetz dual of $[D] \in H_2(W, \partial W)$ is a 1–cocycle that we will denote $\eta_0 \in H^1(W)$. It is easy to check that η_0 is in the kernel of the restriction $r_1 : H^1(W) \to H^1(\Sigma_g)$, so we may complete η_0 to a basis $\eta_0, \eta_1, \ldots, \eta_{2g}$ of $H^1(W)$ with the property that $\xi_1 := r_1(\eta_1), \ldots,\ \xi_{2g} := r_1(\eta_{2g})$ form a basis for $H^1(\Sigma_g)$. Since the restriction $r_2 : H^1(W) \to H^1(\Sigma_{g+1})$ is injective, we know $\bar{\xi}_0 := r_2(\eta_0), \ldots,\ \bar{\xi}_{2g} := r_2(\eta_{2g})$ are linearly independent; note that $r_2(\eta_0)$ is just c^*, the Poincaré dual of c.

The choice of basis η_j with its restrictions ξ_j, $\bar{\xi}_j$ gives rise to an inclusion $i\colon H^1(\Sigma_g) \to H^1(\Sigma_{g+1})$ in the obvious way, namely $i(\xi_j) = \bar{\xi}_j$. One may check that this map is independent of the choice of basis $\{\eta_j\}$ for $H^1(W)$ having η_0 as above. From the decomposition (12), we can extend i to an inclusion $i\colon H^*(\Sigma_g^{(n)}) \hookrightarrow H^*(\Sigma_{g+1}^{(n)})$. Having produced this inclusion, we now proceed to suppress it from the notation, in particular in the following theorem.

Theorem 4.2 (Donaldson) *In this situation, and with σ and n as previously, the map κ_n corresponding to the elementary cobordism W is given by*

$$\kappa_n(\alpha) = c^* \wedge \alpha.$$

If $\bar{W}$ is the "opposite" cobordism between Σ_{g+1} and Σ_g, the corresponding κ_n is given by the contraction

$$\kappa_n(\beta) = \iota_{c^*}\beta,$$

where contraction is defined using the intersection pairing on $H^1(\Sigma_{g+1})$.

This result makes the calculation of Seiberg–Witten invariants completely explicit, as we see in the next few sections.

5 Standardization of X

We now return to the situation of the introduction: namely, we consider a closed 3–manifold X having $b_1(X) \geq 1$, with its circle-valued Morse function $\phi\colon X \to S^1$ having no critical points of index 0 or 3, and N critical points of each index 1 and 2. We want to show how to identify X with a "standard" manifold $M(g, N, h)$ that depends only on N and a diffeomorphism h of a Riemann surface of genus $g+N$. This standard manifold will be obtained from two "compression bodies," ie, cobordisms between surfaces incorporating handle additions of all the same index. Two copies of the same compression body can be glued together along their smaller-genus boundary by the identity map, then by a "monodromy" diffeomorphism of the other boundary component to produce a more interesting 3–manifold. Such a manifold lends itself well to analysis using the TQFT from the previous section, as the interaction between the curves c corresponding to each handle is completely controlled by the monodromy. We now will show that every closed oriented 3–manifold X having $b_1(X) > 0$ can be realized as such a glued-up union of compression bodies.

To begin with, we fix a closed oriented genus 0 surface Σ_0 (that is, a standard 2–sphere) with an orientation-preserving embedding $\psi_{0,0}: S^0 \times D^2 \to \Sigma_0$. Here we write $D^n = \{x \in \mathbb{R}^n \,||x| < 1\}$ for the unit disk in $\mathbb{R}^n$. There is a standard way to perform surgery on the image of $\psi_{0,0}$ (see [12]) to obtain a new surface Σ_1 of genus 1 and an orientation-preserving embedding $\psi_{1,1}: S^1 \times D^1 \to \Sigma_1$. In fact we can get a cobordism $(W_{0,1}, \Sigma_0, \Sigma_1)$ with a "gradient-like vector field" ξ for a Morse function $f\colon W_{0,1} \to [0,1]$. Here $f^{-1}(0) = \Sigma_0$, $f^{-1}(1) = \Sigma_1$, and f has a single critical point p of index 1 with $f(p) = \frac{1}{2}$. We have that $\xi[f] > 0$ away from p and that in local coordinates near p, $f = \frac{1}{2} - {x_1}^2 + {x_2}^2 + {x_3}^2$ and $\xi = -x_1\frac{\partial}{\partial x_1} + x_2\frac{\partial}{\partial x_2} + x_3\frac{\partial}{\partial x_3}$. The downward flow of ξ from p intersects Σ_0 in $\psi_{0,0}(S^0 \times 0)$ and the upward flow intersects Σ_1 in $\psi_{1,1}(S^1 \times 0)$.

Choose an embedding $\psi_{0,1}\colon S^0 \times D^2 \to \Sigma_1$ whose image is disjoint from $\psi_{1,1}(S^1\times D^1)$. Then we can repeat the process above to get another cobordism $(W_{1,2}, \Sigma_1, \Sigma_2)$ with Morse function $f\colon W_{1,2} \to [1,2]$ having a single critical point of index 1 at level $\frac{3}{2}$, and gradient-like vector field ξ as before.

Continuing in this way, we get a sequence of cobordisms $(W_{g,g+1}, \Sigma_g, \Sigma_{g+1})$ between surfaces of genus difference 1, with Morse functions $f\colon W_{g,g+1} \to [g, g+1]$ and gradient-like vector fields ξ. To each Σ_g, $g \geq 1$, is also associated a pair of embeddings $\psi_{i,g}\colon S^i \times D^{2-i} \to \Sigma_g$, $i = 0, 1$. These embeddings have disjoint images, and are orientation-preserving with respect to the given, fixed orientations on the Σ_g. Note that the orientation on Σ_g induced by $W_{g,g+1}$ is opposite to the given one, so the map $\psi_{0,g}\colon S^0 \times D^2 \to -\Sigma_g = \partial_- W_{g,g+1}$ is orientation-reversing.

Since the surfaces Σ_g are all standard, we have a natural way to compose $W_{g-1,g}$ and $W_{g,g+1}$ to produce a cobordism $W_{g-1,g+1} = W_{g-1,g} + W_{g,g+1}$ with a Morse function to $[g-1, g+1]$ having two index-1 critical points. Furthermore, by replacing f by $-f$ we can obtain cobordisms $(W_{g+1,g}, \Sigma_{g+1}, \Sigma_g)$ with Morse functions having a single critical point of index 2, and these cobordisms may be naturally composed with each other or with the original index-1 cobordisms obtained before (after appropriately adjusting the values of the corresponding Morse functions), whenever such composition makes sense. We may think of $W_{g+1,g}$ as being simply $W_{g,g+1}$ with the opposite orientation.

In particular, we can fix integers $g, N \geq 0$ and proceed as follows. Beginning with Σ_{g+N}, compose the cobordisms $W_{g+N,g+N-1}, \ldots, W_{g+1,g}$ to form a "standard" compression body, and glue this with the composition $W_{g,g+1} + \cdots + W_{g+N-1,g+N}$ using the identity map on Σ_g. The result is a cobordism $(W, \Sigma_{g+N}, \Sigma_{g+N})$ and a Morse function $f\colon W \to \mathbb{R}$ that we may rescale to have range $[-N, N]$, having N critical points each of index 1 and 2. By our construction, the first half of this cobordism, $W_{g+N,g}$, is identical with the second half, $W_{g,g+N}$: they differ only in their choice of Morse function and associated gradient-like vector field.

Now, by our construction the circles $\psi_{1,g+k}\colon S^1 \times 0 \to f^{-1}(-k) = \Sigma_{g+k} \subset W$, $1 \leq k \leq N$, all survive to Σ_{g+N} under downward flow of ξ. This is because the images of $\psi_{1,q}$ and $\psi_{0,q}$ are disjoint for all q. Thus on the "lower" copy of Σ_{g+N} we have N disjoint primitive circles $c_1, \ldots, c_N$ that, under upward flow of ξ, each converge to an index 2 critical point. Similarly, (since $W_{g,g+N} = W_{g+N,g}$) the circles $\psi_{1,l}\colon S^1 \times 0 \to f^{-1}(k) = \Sigma_{g+k} \subset W$, $1 \leq k \leq N$, survive to Σ_{g+N} under upward flow of ξ, and intersect the "upper" copy of Σ_{g+N} in the circles $c_1, \ldots, c_N$.

Now suppose $h\colon \partial_+W = \Sigma_{g+N} \to \Sigma_{g+N} = -\partial_-W$ is a diffeomorphism; then we can use h to identify the boundaries $f^{-1}(-N)$, $f^{-1}(N)$ of W, and produce a manifold that we will denote by $M(g,N,h)$. Note that this manifold is entirely determined by the isotopy class of the map h, and that if h preserves orientation then $M(g,N,h)$ is an orientable manifold having $b_1 \geq 1$.

Theorem 5.1 *Let X be a closed oriented 3–manifold and $\phi\colon X \to S^1$ a circle-valued Morse function with no critical points of index 0 or 3, and with N critical points each of index 1 and 2. Assume that $[\phi] \in H^1(X;\mathbb{Z})$ is of infinite order and indivisible. Arrange that $0 < \arg\phi(p) < \pi$ for p an index 1 critical point and $\pi < \arg\phi(q) < 2\pi$ for q an index 2 critical point, and let $S_g = \phi^{-1}(1)$, where S_g has genus g. Then X is diffeomorphic to $M(g,N,h)$ for some $h\colon \Sigma_{g+N} \to \Sigma_{g+N}$ as above.*

Note that S_g has by construction the smallest genus among smooth slices for f.

Proof By assumption -1 is a regular value of ϕ, so $S_{g+N} = \phi^{-1}(-1)$ is a smooth orientable submanifold of X; it is easy to see that S_{g+N} is a closed surface of genus $g+N$. Cut X along S_{g+N}; then we obtain a cobordism (W_ϕ, S_-, S_+) between two copies $S_\pm$ of S_{g+N}, and a Morse function $f\colon W_\phi \to [-\pi,\pi]$ induced by $\arg\phi$. The critical points of f are exactly those of ϕ (with the same index), and by our arrangement of critical points we have that $f(q) < 0$ for any index 2 critical point q and $f(p) > 0$ for any index 1 critical point p. It is well-known that we can arrange for the critical points of f to have distinct values, and that in this case W_ϕ is diffeomorphic to a composition of elementary cobordisms, each containing a single critical point of f. For convenience we rescale f so that its image is the interval $[-N,N]$ and the critical values of f are the half-integers between $-N$ and N. Orient each smooth level set $f^{-1}(x)$ by declaring that a basis for the tangent space of $f^{-1}(x)$ is positively oriented if a gradient-like vector field for f followed by that basis is a positive basis for the tangent space of W_ϕ.

We will show that W_ϕ can be standardized by working "from the middle out." Choose a gradient-like vector field ξ_f for f, and consider $S_g = f^{-1}(0)$—the "middle level" of W_ϕ, corresponding to $\phi^{-1}(1)$. There is exactly one critical point of f in the region $f^{-1}([0,1])$, of index 1, and as above ξ_f determines a "characteristic embedding" $\theta_{0,g}\colon S^0 \times D^2 \to S_g$. Choose a diffeomorphism $\Theta_0\colon S_g \to \Sigma_g$ such that $\Theta_0 \circ \theta_{0,g} = \psi_{0,g}$; then it follows from [12], Theorem 3.13, that $f^{-1}([0,1])$ is diffeomorphic to $W_{g,g+1}$ by some diffeomorphism Θ sending ξ_f to ξ. (Recall that ξ is the gradient-like vector field fixed on $W_{g,g+1}$.)

Let $\Theta_1\colon S_{g+1} \to \Sigma_{g+1}$ be the restriction of Θ to $S_{g+1} = f^{-1}(1)$, and let $\mu_{0,g+1} = \Theta_1^{-1} \circ \psi_{0,g+1}\colon S^0 \times D^2 \to S_{g+1}$. Now ξ_f induces an embedding $\theta_{0,g+1}\colon S^0 \times D^2 \to S_{g+1}$, by considering downward flow from the critical point in $f^{-1}([1,2])$. Since any two orientation-preserving diffeomorphisms $D^2 \to D^2$ are isotopic and S_{g+1} is connected, we have that $\mu_{0,g+1}$ and $\theta_{0,g+1}$ are isotopic. It is now a simple matter to modify ξ_f in the region $f^{-1}([1, 1+\epsilon])$ using the isotopy, and arrange that $\theta_{0,g+1} = \mu_{0,g+1}$. Equivalently, $\Theta \circ \theta_{0,g+1} = \psi_{0,g+1}$, so the theorem quoted above shows that $f^{-1}([1,2])$ is diffeomorphic to $W_{g+1,g+2}$. In fact, since the diffeomorphism sends ξ_f to ξ, we get that Θ extends smoothly to a diffeomorphism $f^{-1}([0,2]) \to W_{g,g+2}$.

Continuing in this way, we see that after successive modifications of ξ_f in small neighborhoods of the levels $f^{-1}(k)$, $k = 1, \ldots, N-1$, we obtain a diffeomorphism $\Theta\colon f^{-1}([0,N]) \to W_{g,g+N}$ with $\Theta_*\xi_f = \xi$.

The procedure is entirely analogous when we turn to the "lower half" of W_ϕ, but the picture is upside-down. We have the diffeomorphism $\Theta_0\colon S_g \to \Sigma_g$, but before we can extend it to a diffeomorphism $\Theta\colon f^{-1}([-1,0]) \to W_{g+1,g}$ we must again make sure the characteristic embeddings match. That is, consider the map $\theta'_{0,g}\colon S^0 \times D^2 \to S_g$ induced by upward flow from the critical point, and compare it to $\Theta_0^{-1} \circ \psi_{0,g}$. As before we can isotope ξ_f in (an open subset whose closure is contained in) the region $f^{-1}([-\epsilon, 0])$ so that these embeddings agree, and we then get the desired extension of Θ to $f^{-1}([-1,N])$. Then the procedure is just as before: alter ξ_f at each step to make the characteristic embeddings agree, and extend Θ one critical point at a time.

Thus $\Theta\colon W_\phi \cong W = W_{g+N,g+N-1} + \cdots + W_{g+1,g} + W_{g,g+1} + \cdots + W_{g+N-1,g+N}$. Since W_ϕ was obtained by cutting X, it comes with an identification $\iota\colon S_+ \to S_-$. Hence $X \cong M(g,N,h)$ where $h = \Theta \circ \iota \circ \Theta^{-1}\colon \Sigma_{g+N} \to \Sigma_{g+N}$. □

Remark 5.2 The identification $X \cong M(g,N,h)$ is not canonical, as it depends on the initial choice of diffeomorphism $\phi^{-1}(1) \cong \Sigma_g$, the final gradient-like vector field on W_ϕ used to produce Θ, as well as the function ϕ. As with a Heegard decomposition, however, it is the existence of such a structure that is important.

6 Preliminary calculations

This section collects a few lemmata that we will use in the proof of Theorem 2.4. Our main object here is to make the quantity $[\zeta(F)\det(d)]_n$ a bit more explicit.

We work in the standardized setup of the previous section, identifying X with $M(g,N,h)$. The motivation for doing so is mainly that our invariants are purely algebraic—ie, homological—and the standardized situation is very easy to deal with on this level.

Choose a metric k on $X = M(g,N,h)$; then gradient flow with respect to k on $(W,\Sigma_{g+N},\Sigma_{g+N})$ determines curves $\{c_i\}_{i=1}^N$ and $\{d_j\}_{j=1}^N$ on Σ_{g+N}, namely c_i is the intersection of the descending manifold of the ith index-2 critical point with the lower copy of Σ_{g+N} and d_j is the intersection of the ascending manifold of the jth index-1 critical point with the upper copy of Σ_{g+N}.

Definition 6.1 The pair (k,ϕ) consisting of a metric k on X together with the Morse function $\phi\colon X\to S^1$ is said to be *symmetric* if the following conditions are satisfied. Arrange the critical points of ϕ as in Theorem 5.1, so that all critical points have distinct values. Write W_ϕ for the cobordism $X\setminus\phi^{-1}(-1)$, and $f\colon W_\phi\to[-N,N]$ for the (rescaled) Morse function induced by ϕ as in the proof of Theorem 5.1. Write I for the (orientation-reversing) involution obtained by swapping the factors in the expression $W_\phi\cong W_{g+N,g}\cup W_{g,g+N}$. We require:

(1) $I^*f=-f$.

(2) For every $x\in W_{g+N,g}$ we have $(\nabla f)_{I(x)} = -I_*(\nabla f)_x$.

Symmetric pairs (k,ϕ) always exist: choose any metric on X, and then in the construction used in the proof of Theorem 5.1, take our gradient-like vector field ξ_f to be a multiple of the gradient of f with respect to that metric. It is a straightforward exercise to see that the isotopies of ξ_f needed in that proof may be obtained by modifications of the metric.

We use the term "symmetric" here because the gradient flows of the Morse function f on the portions $W_{g+N,g}$ and $W_{g,g+N}$ are mirror images of each other. We will also say that the flow of ∇f or of $\nabla\phi$ is symmetric in this case.

Suppose $M(g,N,h)$ is endowed with a symmetric pair, and consider the calculation of $\zeta(F)\tau(M^*)$ in this case. Recall that F is the return map of the flow of $\nabla\phi$ from Σ_g to itself (though F is only partially defined due to the existence of critical points). Because of the symmetry of the flow, it is easy to see that:

(I) The fixed points of iterates F^k are in 1–1 correspondence with fixed points of iterates h^k of the gluing map in the construction of W, and the Lefschetz signs of the fixed points agree. Indeed, if h is sufficiently generic, we can assume that the set of fixed points of h^k for $1\leq k\leq n$ (an arbitrary, but fixed, n) occur away from the d_j (which agree with the c_i under the identification I by symmetry).

(II) The (i,j)th entry of the matrix of $d_M:\ M^1 \to M^2$ in the Morse complex is given by the series

$$\sum_{k\geq 1} \langle h^{k^*} c_i, c_j\rangle t^{k-1}, \tag{13}$$

where $\langle\cdot,\cdot\rangle$ denotes the cup product pairing on $H^1(\Sigma_{g+N},\mathbb{Z})$ and we have identified the curves c_i with the Poincaré duals of the homology classes they represent.

We should remark that a symmetric pair is not *a priori* suitable for calculating the invariant $\zeta(F)\tau(M^*)$ of Hutchings and Lee, since it is not generic. Indeed, for a symmetric flow each index-2 critical point has a pair of upward gradient flow lines into an index-1 critical point. However, this is the only reason the flow is not generic: our plan now is to perturb a symmetric metric to one which does not induce the behavior of the flow just mentioned; then suitable genericity of h guarantees that the flow is Morse–Smale.

Lemma 6.2 *Assume that there are no "short" gradient flow lines between critical points, that is, every flow line between critical points intersects Σ_g at least once. Given a symmetric pair (g_0,ϕ) on $M(g,N,h)$ and suitable genericity hypotheses on h, there exists a C^0–small perturbation of g_0 to a metric $\tilde{g}$ such that for given $n\geq 0$*

1. *The gradient flow of ϕ with respect to $\tilde{g}$ is Morse–Smale; in particular the hypotheses of Theorem 2.3 are satisfied.*
2. *The quantity $[\zeta(F)\tau(M^*)]_m$, $m\leq n$ does not change under this perturbation.*

We defer the proof of this result to Section 9.

Remark 6.3 We can always arrange that there are no short gradient flow lines, at the expense of increasing $g = \text{genus}(\Sigma_g)$. To see this, begin with X and $\phi\colon X\to S^1$ as before, with $\Sigma_g = \phi^{-1}(1)$ and the critical points arranged according to index. Every gradient flow line then intersects Σ_{g+N}. Now rearrange the critical points by an isotopy of ϕ that is constant near Σ_{g+N} so that the index-1 points occur in the region $\phi^{-1}(\{e^{i\theta}|\pi<\theta<2\pi\})$ and the index-2 points in the complementary region. This involves moving all $2N$ of the critical points past Σ_g, and therefore increasing the genus of the slice $\phi^{-1}(1)$ to $g+2N$; we still have that every gradient flow line between critical points intersects Σ_{g+N}. Cutting X along this new $\phi^{-1}(1)$ gives a cobordism $\tilde{W}$ between two copies of Σ_{g+2N} and thus standardizes X in the way we need while ensuring that there are no short flows.

Corollary 6.4 *The coefficients of the torsion $\tau(X,\phi)$ may be calculated homologically, as the coefficients of the quantity $\zeta(h)\tau(M_0^*)$ where M_0^* is the Morse complex coming from a symmetric flow.*

That is, we can use properties I and II of symmetric pairs to calculate each coefficient of the right-hand side of (1).

Lemma 6.5 *If the flow of $\nabla\phi$ is symmetric, the torsion $\tau(M^*)$ is represented by a polynomial whose kth coefficient is given by*

$$[\tau(M^*)]_k = \sum_{\substack{s_1+\cdots+s_N=k \\ \sigma\in\mathfrak{S}_N}} (-1)^{\mathrm{sgn}(\sigma)}\langle h^{s_1 *}c_1, c_{\sigma(1)}\rangle\cdots\langle h^{s_N *}c_N, c_{\sigma(N)}\rangle.$$

Proof Since there are only two nonzero terms in the Morse complex, the torsion is represented by the determinant of the differential $d_M:\ M^1\to M^2$. Our task is to calculate a single coefficient of the determinant of this matrix of polynomials. It will be convenient to multiply the matrix of d_M by t; this multiplies $\det(d_M)$ by t^N, but $t^N\det(d_M)$ is still a representative for $\tau(M^*)$. Multiplying formula (13) by t shows

$$\begin{aligned} t^N\det(d_M) &= \sum_{\sigma\in\mathfrak{S}_N}(-1)^{\mathrm{sgn}(\sigma)}\prod_i\left(\sum_k\langle h^{k*}c_i, c_{\sigma(i)}\rangle t^k\right) \\ &= \sum_k\sum_{\sigma\in\mathfrak{S}_N}\sum_{s_1+\cdots s_N=k}(-1)^{\mathrm{sgn}(\sigma)}\left(\prod_i\langle h^{s_i *}c_i, c_{\sigma(i)}\rangle\right)t^k \end{aligned}$$

and the result follows. □

7 Proof of Theorem 2.4

We are now in a position to explicitly calculate $\mathrm{Tr}\,\kappa_n$ using Theorem 4.2 and as a result prove Theorem 2.4, assuming throughout that X is identified with $M(g,N,h)$ and the flow of $\nabla\phi$ is symmetric. Indeed, fix the nonnegative integer n as in Section 4 and consider the cobordism W_ϕ as above, identified with a composition of standard elementary cobordisms. Using Theorem 4.2 we see that the first half of the cobordism, $W_{g+N,g}=f^{-1}([0,N])$, induces the map:

$$\begin{aligned} A_1:\ H^*(\Sigma_{g+N}^{(n+N)}) &\to H^*(\Sigma_g^{(n)}) \\ \alpha &\mapsto \iota_{c_N^*}\cdots\iota_{c_1^*}\,\alpha \end{aligned}$$

The second half, $f^{-1}([N, 2N])$, induces:

$$\begin{array}{rcl} A_2:\ H^*(\Sigma_g^{(n)}) & \to & H^*(\Sigma_{g+N}^{(n+N)}) \\ \beta & \mapsto & c_1^* \wedge \cdots \wedge c_N^* \wedge \beta \end{array}$$

To obtain the map κ_n we compose the above with the gluing map h^* acting on the symmetric power $\Sigma_{g+N}^{(n+N)}$. The alternating trace $\operatorname{Tr} \kappa_n$ is then given by $\operatorname{Tr}(h^* \circ A_2 \circ A_1)$.

Following MacDonald [9], we can take a monomial basis for $H^*(\Sigma_g^{(n)})$. Explicitly, if $\{x_i\}_{i=1}^{2g}$ is a symplectic basis for $H^1(\Sigma)$ having $x_i \cup x_{j+g} = \delta_{ij}$ for $1 \leq i, j \leq g$, and $x_i \cup x_j = 0$ for other values of i and j, $1 \leq i < j \leq 2g$, and y denotes the generator of $H^2(\Sigma_g)$ coming from the orientation class, the expression (12) shows that the set

$$B_g^{(n)} = \{\alpha\} = \{x_I y^q = x_{i_1} \wedge \cdots \wedge x_{i_k} \cdot y^q | I = \{i_1 < \ldots < i_k\} \subset \{1, \ldots, 2g\}\},$$

where $q = 1, \ldots, n$ and $k = 0, \ldots, n-q$, forms a basis for $H^*(\Sigma_g^{(n)})$. We take $H^*(\Sigma_{g+k}^{(n+k)})$ to have similar bases $B_{g+k}^{(n+k)}$, using the images of the x_i under the inclusion $i\colon H^1(\Sigma_{g+k-1}) \to H^1(\Sigma_{g+k})$ constructed in section 4, the (Poincaré duals of the) curves $c_1, \ldots, c_k$, and (the Poincaré duals of) some chosen dual curves d_i to the c_i as a basis for $H^1(\Sigma_{g+k})$. Our convention is that $c_i \cup d_j = \delta_{ij}$, where we now identify c_i, d_j with their Poincaré duals.

The dual basis for $B_{g+k}^{(n+k)}$ under the cup product pairing will be denoted $B_{n+k}^\circ = \{\alpha^\circ\}$. Thus $\alpha^\circ \cup \beta = \delta_{\alpha\beta}$ for basis elements α and β. By abuse of notation, we will write $B_g^{(n)} \subset B_h^{(m)}$ for $g \leq h$ and $n \leq m$; this makes use of the inclusions on $H^1(\Sigma_g)$ induced by our standard cobordisms.

With these conventions, we can write:

$$\begin{aligned} \operatorname{Tr} \kappa_n &= \sum_{\alpha \in B_{g+N}^{(n+N)}} (-1)^{\deg(\alpha)} \alpha^\circ \cup h^* \circ A_2 \circ A_1(\alpha) \\ &= \sum_{\alpha \in B_{g+N}^{(n+N)}} (-1)^{\deg(\alpha)} \alpha^\circ \cup h^*(c_1 \wedge \cdots \wedge c_N\, \iota_{c_N} \cdots \iota_{c_1} \alpha) \end{aligned}$$

For a term in this sum to be nonzero, α must be of a particular form. Namely, we must be able to write $\alpha = d_1 \wedge \cdots \wedge d_N \wedge \beta$ for some $\beta \in B_g^{(n)}$. The sum then can be written:

$$= \sum_{\beta \in B_g^{(n)}} (-1)^{\deg(\beta)+N} (d_1 \wedge \cdots \wedge d_N \wedge \beta)^\circ \cup h^*(c_1 \wedge \cdots \wedge c_N \wedge \beta) \quad (14)$$

In words, this expression asks us to find the coefficient of $d_1 \wedge \cdots \wedge d_N \wedge \beta$ in the basis expression of $h^*(c_1 \wedge \cdots \wedge c_N \wedge \beta)$, and add up the results with particular signs. Our task is to express this coefficient in terms of intersection data among the c_i and the Lefschetz numbers of h acting on the various symmetric powers of Σ_g.

Consider the term of (14) corresponding to $\beta = x_I y^q$ for $I = \{i_1, ..., i_k\} \subset \{1, ..., 2g\}$ and $x_I = x_{i_1} \wedge \cdots \wedge x_{i_k}$. The coefficient of $d_1 \wedge \cdots \wedge d_N \wedge x_I y^q$ in the basis expression of $h^*(c_1 \wedge \cdots \wedge c_N \wedge x_I y^q)$ is computed by pairing each of $\{c_1, ..., c_N, x_{i_1}, ..., x_{i_k}\}$ with each of $\{d_1, ..., d_N, x_{i_1}, ..., x_{i_k}\}$ in every possible way, and summing the results with signs corresponding to the permutation involved. To make the notation a bit more compact, for given I let $\bar{I} = \{1, ..., N, i_1, ..., i_k\}$ and write the elements of $\bar{I}$ as $\{\bar{\imath}_m\}_{m=1}^{N+k}$. Likewise, set $\bar{I}' = \{N+1, ..., 2N, i_1, ..., i_k\} = \{\bar{\imath}'_1, ..., \bar{\imath}'_{N+k}\}$.

Write $\{\xi_i\}_{i=1}^{2N+2g}$ for our basis of $H^1(\Sigma_{g+N})$:

$$\xi_1 = c_1, \quad \cdots, \quad \xi_N = c_N,\ \xi_{N+1} = d_1, \quad \cdots, \quad \xi_{2N} = d_N$$
$$\xi_{2N+1} = x_1, \quad \cdots, \quad \xi_{2N+2g} = x_{2g}$$

and let $\{\xi'_i\}$ be the dual basis: $\langle \xi_i, \xi'_j \rangle = \delta_{ij}$. Define $\zeta_i = h^*(\xi_i)$.

Then since $\deg \beta = |I| = k$ modulo 2, the term of (14) corresponding to $\beta = x_I y^q$ is

$$(-1)^{k+N} \sum_{\sigma \in \mathfrak{S}_{k+N}} (-1)^{\mathrm{sgn}(\sigma)} \langle \zeta_{\bar{\imath}_1}, \xi'_{\bar{\imath}'_{\sigma(1)}} \rangle \cdots \langle \zeta_{\bar{\imath}_{k+N}}, \xi'_{\bar{\imath}'_{\sigma(k+N)}} \rangle, \tag{15}$$

and (14) becomes

$$\operatorname{Tr} \kappa_n = \sum_{k=0}^{\min(n, 2g+2N)} (2(n-k)+1) \sum_{\substack{I \subset \{2N+1, \ldots, 2N+2g\} \\ |I|=k}} [\text{formula (15)}]. \tag{16}$$

Here we are using the fact that for each $k = 0, \ldots, \min(n, 2g+2N)$ the space $\Lambda^k H^1(\Sigma_{g+N})$ appears in $H^*(\Sigma^{(n)})$ precisely $2(n-k)+1$ times, each in cohomology groups of all the same parity.

Note that from (14) we can see that the result is unchanged if we allow not just sets $I \subset \{2N+1, \ldots, 2N+2g\}$ in our sum as above, but extend the sum to include sets $I = \{i_1, \ldots, i_k\}$, where $i_1 \leq \cdots \leq i_k$ and each $i_j \in \{1, \ldots, 2N+2g\}$. That is, we can allow I to include indices referring to the c_i or d_i, and allow repeats: terms corresponding to such I contribute 0 to the sum. Likewise, we may assume that the sum in (16) is over $k = 0, \ldots, n$ since values of k larger than $2g+2N$ necessarily involve repetitions in $\bar{I}$.

Consider the permutations $\sigma \in \mathfrak{S}_{k+N}$ used in the above. The fact that the first N elements of $\bar{I}$ and $\bar{I}'$ are distinguished (corresponding to the c_j and d_j, respectively) gives such permutations an additional structure. Indeed, writing $A = \{1, ..., N\} \subset \{1, ..., N+k\}$, let $\bar{A}$ denote the orbit of A under powers of σ, and set $B = \{1, ..., N+k\} \setminus \bar{A}$. Then σ factors into a product $\sigma = \rho \cdot \tau$ where $\rho = \sigma|_{\bar{A}}$ and $\tau = \sigma|_B$. By construction, ρ has the property that the orbit of A under ρ is all of $\bar{A}$. Given any integers $0 \le m \le M$, we let $\mathfrak{S}_{M;m}$ denote the collection of permutations α of $\{1, ..., M\}$ such that the orbit of $\{1, ..., m\}$ under powers of α is all of $\{1, ..., M\}$. The discussion above can be summarized by saying that if $\bar{A} = \{a_1, ..., a_N, a_{N+1}, ..., a_{N+r}\}$ (where $a_i = i$ for $i = 1, ..., N$) and $B = \{b_1, ..., b_t\}$ then σ preserves each of $\bar{A}$ and B, and $\sigma(\bar{A}) = \{a_{\rho(1)}, ..., a_{\rho(N+r)}\}$, $\sigma(B) = \{b_{\tau(1)}, ..., b_{\tau(t)}\}$ for some $\rho \in \mathfrak{S}_{N+r;N}$, $\tau \in \mathfrak{S}_t$. Furthermore, $\mathrm{sgn}(\sigma) = \mathrm{sgn}(\rho) + \mathrm{sgn}(\tau) \mod 2$.

Finally, for $\rho \in \mathfrak{S}_{N+r;N}$ as above, we define

$$s_i = \min\{m > 0 | \rho^m(i) \in \{1, ..., N\}\}.$$

The definition of $\mathfrak{S}_{N+r;N}$ implies that $\sum_{i=1}^{N} s_i = r + N$.

In (16) we are asked to sum over all sets I with $|I| = k$ and all permutations $\sigma \in \mathfrak{S}_{N+k}$ of the subscripts of $\bar{I}$ and $\bar{I}'$. From the preceding remarks, this is equivalent to taking a sum over all sets $\bar{A} \supset \{1, ..., N\}$ and B with $|\bar{A}| + |B| = N+k$, and all permutations ρ and τ, $\rho \in \mathfrak{S}_{N+r;N}$, $\tau \in \mathfrak{S}_t$ (where $|\bar{A}| = N+r$, $|B| = t$). Since we are to sum over all I and k and allow repetitions, we may replace $\bar{I}$ by $\bar{A} \cup B$, meaning we take the sum over all $\bar{A}$ and B and all ρ and τ as above, and eliminate reference to I. Thus, we replace $\xi_{\bar{\imath}_{a_j}}$ by ξ_{a_j} and $\xi_{\bar{\imath}'_{a_j}}$ by $\xi_{a'_j}$ if we define $\bar{A}' = \{N+1, ..., 2N\} \cup (\bar{A} \setminus \{1, ..., N\})$. (Put another way, pairs $(\bar{I}, \sigma)$ are in 1–1 correspondence with 4–tuples $(\bar{A}, B, \rho, \tau)$.) Then we can write $\mathrm{Tr}\, \kappa_n$ as:

$$\sum_{k=0}^{n} (2(n-k)+1)(-1)^{k+N} \sum_{\substack{\bar{A}, B \\ |\bar{A}|+|B|=k+N}} \sum_{\substack{\rho \in \mathfrak{S}_{|A|;N} \\ \tau \in \mathfrak{S}_{|B|}}} (-1)^{\mathrm{sgn}(\rho)} \prod_{\substack{i=1,\dots,N \\ m=0,\dots,s_i-1}} \langle \zeta_{a_{\rho^m(i)}}, \xi'_{a'_{\rho^{m+1}(i)}} \rangle$$
$$\times (-1)^{\mathrm{sgn}(\tau)} \prod_{r=1}^{|B|} \langle \zeta_{b_r}, \xi'_{b_{\tau(r)}} \rangle$$

Carrying out the sum over all B of a given size t and all permutations τ, this becomes:

$$\sum_{k=0}^{n}\sum_{\substack{\bar{A};|\bar{A}|=k+N-t\\ t=0,\dots,k}}\sum_{\rho\in\mathfrak{S}_{|A|;N}}(-1)^{\operatorname{sgn}(\rho)+k+N}(2(n-k)+1)\prod_{\substack{i=1,\dots,N\\ m=0,\dots,s_i-1}}\langle\zeta_{a_{\rho^m(i)}},\xi'_{a'_{\rho^{m+1}(i)}}\rangle$$
$$\times\operatorname{tr}(h^*|_{\Lambda^t H^1(\Sigma_{g+N})})$$

Reordering the summations so that the sum over $\bar{A}$ is on the outside and the sum on t is next, we find that $k=|\bar{A}|-N+t$ and the expression becomes:

$$\sum_{\substack{\bar{A}\\ |\bar{A}|-N=0,\dots,n}}\sum_{t=0}^{n-(|\bar{A}|-N)}(-1)^{|\bar{A}|+\operatorname{sgn}(\rho)}\sum_{\rho\in\mathfrak{S}_{|A|;N}}\prod_{\substack{i=1,\dots,N\\ m=0,\dots,s_i-1}}\langle\zeta_{a_{\rho^m(i)}},\xi'_{a'_{\rho^{m+1}(i)}}\rangle$$
$$\times(-1)^t(2[n-(t-(|\bar{A}|-N))]+1)\operatorname{tr}(h^*|_{\Lambda^t H^1(\Sigma_{g+N})})$$

Again using the fact that $\Lambda^t H^1(\Sigma_{g+N})$ appears exactly $2(|\bar{A}|-t)+1$ times in $H^*(\Sigma^{(|\bar{A}|-N)})$ and writing $|\bar{A}|=N+r$, we can carry out the sum over t to get that $\operatorname{Tr}\kappa_n$ is:

$$\sum_{r=0}^{n}\left[\sum_{\substack{\bar{A}\\ |\bar{A}|-N=r}}\sum_{\rho\in\mathfrak{S}_{r+N;N}}(-1)^{\operatorname{sgn}(\rho)+|\bar{A}|}\prod_{\substack{i=1,\dots,N\\ m=0,\dots,s_i-1}}\langle\zeta_{a_{\rho^m(i)}},\xi'_{a'_{\rho^{m+1}(i)}}\rangle\right]\cdot L(h^{(n-r)})$$

Here $L(h^{(n-r)})$ is the Lefschetz number of h acting on the $(n-r)$th symmetric power of Σ_{g+N} which, as remarked in (4), is the $(n-r)$th coefficient of $\zeta(h)$. In view of Corollary 6.4, we will be done if we show that the quantity in brackets is the rth coefficient of the representative $t^N\det(d_M)$ of $\tau(M^*)$. Recalling the definition of $\bar{A}$, ζ_i, and ξ_i, note that the terms that we are summing in the brackets above are products over all i of formulae that look like

$$\langle c_i,\xi'_{a'_{\rho(i)}}\rangle\langle h^*(\xi_{a_{\rho(i)}}),\xi'_{a'_{\rho^2(i)}}\rangle\cdots\langle h^*(\xi_{\rho^{s_i-1}(i)}),c_{\tilde{\rho}(i)}\rangle \tag{17}$$

where $\tilde{\rho}(i)\in\{1,\dots,N\}$ is defined to be $\rho^{s_i}(i)$. If we sum this quantity over all $\bar{A}$ and all ρ that induce the same permutation $\tilde{\rho}$ of $\{1,\dots,N\}$, we find that (17) becomes simply $\langle h^{*s_i}(c_i),c_{\tilde{\rho}(i)}\rangle$. Therefore the quantity in brackets is a sum of terms like

$$(-1)^{\operatorname{sgn}(\rho)+r+N}\langle h^{*s_1}c_1,c_{\tilde{\rho}(1)}\rangle\cdots\langle h^{*s_N}(c_N),c_{\tilde{\rho}(N)}\rangle,$$

where we have fixed $s_1,\dots,s_N$ and $\tilde{\rho}$ and carried out the sum over all ρ such that

(1) $\min\{m>0|\rho^m(i)\in\{1,\dots,N\}\}=s_i$, and
(2) The permutation $i\mapsto\rho^{s_i}(i)$ of $\{1,\dots,N\}$ is $\tilde{\rho}$.

(As we will see, $\operatorname{sgn}(\rho)$ depends only on $\tilde\rho$ and $|\bar A|$.) It remains to sum over partitions $s_1+\cdots+s_N$ of $s=|\bar A|=r+N$ and over permutations $\tilde\rho$. But from Corollary 6.4 and Lemma 6.5, the result of those two summations is precisely $[\tau(M^*)]_r$, if we can see just that $\operatorname{sgn}(\tilde\rho)=\operatorname{sgn}(\rho)+|\bar A| \bmod 2$. That is the content of the next lemma.

Lemma 7.1 *Let $A=\{1,\dots,N\}$ and $\bar A=\{1,\dots,s\}$ for some $s\ge N$. Let $\rho\in\mathfrak{S}_{s;N}$ and define*

$$\tilde\rho(i)\in\mathfrak{S}_N,\ \tilde\rho(i)=\rho^{s_i}(i)$$

where s_i is defined as above. Then $\operatorname{sgn}(\rho)=\operatorname{sgn}(\tilde\rho)+m$ modulo 2.

Proof Suppose $\rho=\rho_1\cdots\rho_p$ is an expression of ρ as a product of disjoint cycles; we may assume that the initial elements $a_1,\dots,a_p$ of $\rho_1,\dots,\rho_p$ are elements of A since $\rho\in\mathfrak{S}_{m;N}$. For convenience we include any 1–cycles among the ρ_i, noting that the only elements of $\bar A$ that may be fixed under ρ are in A. It is easy to see that cycles in ρ are in 1–1 correspondence with cycles of $\tilde\rho$, so the expression of $\tilde\rho$ as a product of disjoint cycles is $\tilde\rho=\tilde\rho_1\cdots\tilde\rho_p$ where each $\tilde\rho_i$ has a_i as its initial element. For $a\in A$, define

$$\begin{aligned} n(a) &= \min\{m>0 \mid \rho^m(a)\in A\}\\ \tilde n(a) &= \min\{m>0 \mid \tilde\rho^m(a)=a\}.\end{aligned}$$

Note that $n(a_i)=s_i$ for $i=1,...,N$, $\sum s_i=s$, and $\tilde n(a_i)$ is the length of the cycle $\tilde\rho_i$. The cycles ρ_i are of the form

$$\rho_i=(a_i\cdots\tilde\rho(a_i)\cdots\tilde\rho^2(a_i)\cdots\cdots\tilde\rho^{\tilde n(a_i)-1}(a_i)\cdots)$$

where "$\cdots$" stands for some number of elements of $\bar A$. Hence the cycles ρ_i have length

$$l(\rho_i) = \sum_{m=0}^{\tilde n(a_i)-1}\left(n(\tilde\rho^m(a_i))+1\right) = \tilde n(a_i)+\sum_{m=0}^{\tilde n(a_i)-1} n(\tilde\rho^m(a_i)).$$

Modulo 2, then, we have

$$\begin{aligned}\operatorname{sgn}(\rho) &= \sum_{i=1}^p (l(\rho_i)-1)\\ &= \sum_{i=1}^p\left[\left(\tilde n(a_i)+\sum_{m=0}^{\tilde n(a_i)-1} n(\tilde\rho^m(a_i))\right)-1\right]\\ &= \sum_{i=1}^p(\tilde n(a_i)-1)+\sum_{i=1}^p\sum_{m=0}^{\tilde n(a_i)-1} n(\tilde\rho^m(a_i))\\ &= \operatorname{sgn}(\tilde\rho)+s,\end{aligned}$$

since because $\rho \in \mathfrak{S}_{s;N}$ we have $\sum_{i=1}^{p}\sum_{m=0}^{\tilde{n}(a_i)-1} n(\tilde{\rho}^m(a_i)) = \sum_{i=1}^{N} s_i = s$. $\square$

8 Proof of Theorem 2.5

The theorem of Hutchings and Lee quoted at the beginning of this work can be seen as (or more precisely, the logarithmic derivative of formula (1) can be seen as) a kind of Lefschetz fixed-point theorem for partially-defined maps, specifically the return map F, in which the torsion $\tau(M^*)$ appears as a correction term (see [6]). Now, the Lefschetz number of a homeomorphism h of a closed compact manifold M is just the intersection number of the graph of h with the diagonal in $M \times M$; such consideration motivates the proof of Theorem 2.3 in [6]. With the results of Section 5, we can give another construction.

Given $\phi\colon X = M(g,N,h) \to S^1$ our circle-valued Morse function, cut along $\phi^{-1}(-1)$ to obtain a cobordism W_ϕ between two copies of Σ_{g+N}. Write γ_i, $i = 1,\ldots,N$ for the intersection of the ascending manifolds of the index-1 critical points with $\partial_+ W$ and δ_i for the intersection of the descending manifolds of the index-2 critical points with $\partial_- W$. Since the homology classes $[\gamma_i]$ and $[\delta_i]$ are the same (identifying $\partial_+ W = \partial_- W = \Sigma_{g+N}$), we may perturb the curves γ_i and δ_i to be parallel, ie, so that they do not intersect one another (or any other γ_j, δ_j for $j \neq i$ either). Choose a complex structure on Σ_{g+N} and use it to get a complex structure on the symmetric powers $\Sigma_{g+N}^{(k)}$ for each k. Write T_γ for the N–torus $\gamma_1 \times \cdots \times \gamma_N$ and let $T_\delta = \delta_N \times \cdots \times \delta_1$. Define a function

$$\psi\colon T_\gamma \times \Sigma_{g+N}^{(n)} \times T_\delta \to \Sigma_{g+N}^{(n+N)} \times \Sigma_{g+N}^{(n+N)}$$

by mapping the point $(q_1,\ldots,q_N,\sum p_i, q'_N,\ldots,q'_1)$ to $(\sum p_i + \sum q_j, \sum p_i + \sum q'_j)$.

The perhaps unusual-seeming orders on the δ_i and in the domain of ψ are chosen to obtain the correct sign in the sequel.

Proposition 8.1 *ψ is a smooth embedding, and $D = \mathrm{Im}\psi$ is a totally real submanifold of $\Sigma_{g+N}^{(n+N)} \times \Sigma_{g+N}^{(n+N)}$.*

The submanifold D plays the role of the diagonal in the Lefshetz theorem.

Proof That ψ is one-to-one is clear since the γ_i and δ_j are all disjoint. For smoothness, we work locally. Recall that the symmetric power $\Sigma_g^{(k)}$ is locally isomorphic to $\mathbb{C}^{(k)}$, and a global chart on the latter is obtained by mapping a point $\sum w_i$ to the coefficients of the monic polynomial of degree k having zeros at each w_i. Given a point $(\sum p_i + \sum q_j, \sum p_i + \sum q_j')$ of $\mathrm{Im}(\psi)$ we can choose a coordinate chart on Σ_{g+N} containing all the points p_i, q_j, q_j' so that the γ_i and δ_j are described by disjoint curves in $\mathbb{C}$. Thinking of $q_j \in \gamma_j \subset \mathbb{C} \cong \mathbb{C}^{(1)}$ and simlarly for q_j', we have that locally ψ is just the multiplication map:

$$\left((z-q_1),\ldots,(z-q_N),\prod_{i=1}^n (z-p_i),(z-q_1'),\ldots,(z-q_N')\right)$$
$$\mapsto \left(\prod_{i=1}^n (z-p_i)\prod_{j=1}^N (z-q_j),\ \prod_{i=1}^n (z-p_i)\prod_{j=1}^N (z-q_j')\right)$$

It is clear that the coefficients of the polynomials on the right hand side depend smoothly on the coefficients of the one on the left and on the q_j, q_j'.

On the other hand, if $(f(z), g(z))$ are the polynomials whose coefficients give the local coordinates for a point in $\mathrm{Im}(\psi)$, we know that $f(z)$ and $g(z)$ share exactly n roots since the γ_i and δ_j are disjoint. If p_1 is one such shared root then we can write $f(z) = (z-p_1)\tilde{f}(z)$ and similarly for $g(z)$, where $\tilde{f}(z)$ is a monic polynomial of degree $n+N-1$ whose coefficients depend smoothly (by polynomial long division!) on p_1 and the coefficients of f. Continue factoring in this way until $f(z) = f_0(z)\prod_{i=1}^n (z-p_i)$, using the fact that f and g share n roots to find the p_i. Then f_0 is a degree N polynomial having one root on each γ_i, hence having all distinct roots. Those roots (the q_j) therefore depend smoothly on the coefficients of f_0, which in turn depend smoothly on the coefficients of f. Hence D is smoothly embedded.

That D is totally real is also a local calculation, and is a fairly straightforward exercise from the definition. □

We are now ready to prove the "algebraic" portion of Theorem 2.5.

Theorem 8.2 *Let Γ denote the graph of the map $h^{(n+N)}$ induced by the gluing map h on the symmetric product $\Sigma_{g+N}^{(n+N)}$. Then*

$$D.\Gamma = \mathrm{Tr}\,\kappa_n.$$

Proof Using the notation from the previous section, we have that in cohomology the duals of D and Γ are

$$\begin{aligned} D^* &= \sum_{\beta\in B^{(n)}_{g+N}} (-1)^{\epsilon_1(\beta)}(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ)\times(c_1\wedge\cdots\wedge c_N\wedge\beta) \\ \Gamma^* &= \sum_{\alpha\in B^{(n+N)}_{g+N}} (-1)^{\deg(\alpha)}\alpha^\circ\times {h^*}^{-1}(\alpha). \end{aligned}$$

Here $\epsilon_1(\beta) = \deg(\beta)(N+1)+\frac{1}{2}N(N-1)$. Indeed, since the diagonal is the pushforward of the graph by $1\times h^{-1}$, we get that the dual of the graph is the pullback of the diagonal by $1\times h^{-1}$. We will find it convenient to write

$$D^* = \sum_\beta (-1)^{\epsilon_1(\beta)+\epsilon_2(\beta)}(c_1\wedge\cdots\wedge c_N\wedge\beta)\times(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ),$$

by making the substitution $\beta\mapsto\beta^\circ$ in the previous expression. Since $\beta^{\circ\circ}=\pm\beta$, the result is still a sum over the monomial basis with an additional sign denoted by ϵ_2 in the above but which we will not specify.

Therefore the intersection number is

$$\begin{aligned} D^*\cup\Gamma^* = &\sum_{\alpha,\beta}(-1)^{\epsilon_1+\epsilon_2+\epsilon_3(\alpha,\beta)} \\ &(\alpha^\circ\cup(c_1\wedge\cdots\wedge c_N\wedge\beta))\times({h^*}^{-1}\alpha\cup(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ)) \end{aligned} \tag{18}$$

where $\epsilon_3(\alpha,\beta)=\deg(\alpha)(1+\deg(\beta)+N)$. Since this is a sum over a monomial basis α, the first factor in the cross product above vanishes unless $\alpha = c_1\wedge\cdots\wedge c_N\wedge\beta$, and in that case is 1. Therefore $\deg(\alpha)=\deg(\beta)+N$, which gives $\epsilon_3(\alpha,\beta)\equiv 0 \mod 2$, and (18) becomes

$$\begin{aligned} D^*\cup\Gamma^* &= \sum_\beta(-1)^{\epsilon_1+\epsilon_2}{h^*}^{-1}(c_1\wedge\cdots\wedge c_N\wedge\beta)\cup(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ) \\ &= \sum_\beta(-1)^{\epsilon_1+\epsilon_2}(c_1\wedge\cdots\wedge c_N\wedge\beta)\cup h^*(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ) \\ &= \sum_\beta(-1)^{\epsilon_1}(c_1\wedge\cdots\wedge c_N\wedge\beta^\circ)\cup h^*(c_1\wedge\cdots\wedge c_N\wedge\beta) \end{aligned} \tag{19}$$

where we have again used the substitution $\beta\mapsto\beta^\circ$ and therefore cancelled the sign ϵ_2. Now, some calculation using the cup product structure of $H^*(\Sigma^{(n+N)}_{g+N})$ derived in [9] shows that

$$c_1\wedge\cdots\wedge c_N\wedge\beta^\circ = (-1)^{\epsilon_4(\beta)}(d_1\wedge\cdots\wedge d_N\wedge\beta)^\circ.$$

where $\epsilon_4(\beta) = N\deg(\beta)+\frac{1}{2}N(N+1)\equiv\epsilon_1(\beta)+\deg(\beta)+N \mod 2$. Note that $(\cdot)^\circ$ refers to duality in $H^*(\Sigma^{(n)}_{g+N})$ on the left hand side and in $H^*(\Sigma^{(n+N)}_{g+N})$ on the right. Returning with this to (19) gives

$$D^* \cup \Gamma^* = \sum_\beta (-1)^{\deg(\beta)+N} (d_1 \wedge \cdots \wedge d_N \wedge \beta)^\circ \cup h^*(c_1 \wedge \cdots \wedge c_N \wedge \beta),$$

which is $\operatorname{Tr}\kappa_n$ by (14). Theorem 8.2 follows. $\square$

To complete the proof of Theorem 2.5, we recall that we have already shown that D is a totally real submanifold of $\Sigma_{g+N}^{(n+N)} \times \Sigma_{g+N}^{(n+N)}$. The graph of $h^{(n+N)}$, however, is not even smooth unless h is an automorphism of the chosen complex structure of Σ_{g+N}: in general the set-theoretic map induced on a symmetric power by a diffeomorphism of a surface is only Lipschitz continuous. Salamon [16] has shown that if we choose a path of complex structures on Σ between the given one J and $h^*(J)$, we can construct a symplectomorphism of the moduli space $\mathcal{M}(\Sigma, J) \cong \Sigma_{g+N}^{(n+N)}$ that is homotopic to the induced map $h^{(n+N)}$. Hence Γ is homotopic to a Lagrangian submanifold of $\Sigma_{g+N}^{(n+N)} \times -\Sigma_{g+N}^{(n+N)}$. Since Lagrangians are in particular totally real, and since intersection numbers do not change under homotopy, Theorem 2.5 is proved.

9 Proof of Lemma 6.2

We restate the lemma:

Assume that there are no "short" gradient flow lines between critical points, that is, every flow line between critical points intersects Σ_g at least once. Given a symmetric pair (g_0, ϕ) on $M(g, N, h)$ and suitable genericity hypotheses on h, there exists a C^0–small perturbation of g_0 to a metric $\tilde{g}$ such that for given $n \geq 0$

1. *The gradient flow of ϕ with respect to $\tilde{g}$ is Morse–Smale; in particular the hypotheses of Theorem 2.3 are satisfied.*
2. *The quantity $[\zeta(F)\tau(M^*)]_m$, $m \leq n$ does not change under this perturbation.*

Proof Alter g_0 in a small neighborhood of $\Sigma_g \subset M(g, N, h)$ as follows, working in a half-collar neighborhood of Σ_g diffeomorphic to $\Sigma_g \times (-\epsilon, 0]$ using the flow of $\nabla_{g_0}\phi$ to obtain the product structure on this neighborhood.

Let $p_1, \ldots, p_{2N}$ denote the points in which the ascending manifolds (under gradient flow of f with respect to the symmetric metric g_0) of the index-2 critical points intersect Σ_g in W_ϕ. Since g_0 is symmetric, these points are the same as the points $q_1, \dots, q_{2N}$ in which the descending manifolds of the index-1 critical points intersect Σ_g. Let $\mathcal{O}$ denote the union of all closed orbits of $\nabla\phi$ (with respect to g_0) of degree no more than n, and all gradient flow lines connecting index-1 to index-2 critical points. We may assume that this is a finite set. Choose small disjoint coordinate disks U_i around each p_i such that $U_i \cap (\mathcal{O} \cap \Sigma_g) = \emptyset$.

In $U_i \times (-\epsilon, 0]$, we may suppose the Morse function f is given by projection onto the second factor, $(u,t) \mapsto t$, and the metric is a product $g_0 = g_{\Sigma_g} \oplus (1)$. Let X_i be a nonzero constant vector field in the coordinate patch U_i and μ a cutoff function that is equal to 1 near p_i and zero off a small neighborhood of p_i whose closure is in U_i. Let $\nu(t)$ be a bump function that equals 1 near $t = \epsilon/2$ and vanishes near the ends of the interval $(-\epsilon, 0]$. Define the vector field v in the set $U_i \times (-\epsilon, 0]$ by $v(u,t) = \nabla_{g_0}\phi + \nu(t)\mu(u)X(u)$. Now define the metric g_{X_i} in $U_i \times (-\epsilon, 0]$ by declaring that g_{X_i} agrees with g_0 on tangents to slices $U_i \times \{t\}$, but that v is orthogonal to the slices. Thus, with respect to g_{X_i}, the gradient $\nabla\phi$ is given by a multiple of $v(u,t)$ rather than $\partial/\partial t$.

It is easy to see that repelacing g_0 by g_{X_i} in $U_i \times (-\epsilon, 0]$ for each $i = 1, \dots, 2N$ produces a metric g_X for which upward gradient flow of ϕ on W_ϕ does not connect index-2 critical points to index-1 critical points with "short" gradient flow lines. Elimination of gradient flows of ϕ from index-2 to index-1 points that intersect Σ_{g+N} is easily arranged by small perturbation of h, as are transverse intersection of ascending and descending manifolds and nondegeneracy of fixed points of h and its iterates. Hence the new metric g_X satisfies condition (1) of the Lemma.

For condition (2), we must verify that we have neither created nor destroyed either closed orbits of $\nabla\phi$ or flows from index-1 critical points to index-2 critical points. The fact that no such flow lines have been destroyed is assured by our choice of neighborhoods U_i. We now show that we can choose the vector fields X_i such that no fixed points of F^k are created, for $1 \leq k \leq n$.

Let $F_1 : \Sigma_g \to \Sigma_{g+N} = \partial_+ W_\phi$ be the map induced by gradient flow with respect to g_0, defined away from the q_j, and let $F_2 : \Sigma_{g+N} = \partial_- W_\phi \to \Sigma_g$ be the similar map from the bottom of the cobordism, defined away from the c_j. Then the flow map F, with respect to g_0, is given by the composition $F = F_2 \circ h \circ F_1$ where this is defined. The return map with respect to the g_X- gradient, which we will write $\tilde{F}$, is given by F away from the U_i and by $F + cX$ in the coordinates on U_i where c is a nonnegative function on U_i depending on μ and ν, vanishing near ∂U_i.

Consider the graph $\Gamma_{F^k} \subset \Sigma_g \times \Sigma_g$. Since F^k is not defined on all of Σ_g the graph is not closed, nor is its closure a cycle since F^k in general has no continuous extension to all of Σ. Indeed, the boundary of Γ_{F^k} is given by a union of products of "descending slices" (ie, the intersection of a descending manifold of a critical point with Σ_g) with ascending slices. Restrict attention to the neighborhood U of p, where for convenience p denotes any of the $p_1, \dots, p_{2N}$ above. We have chosen U so that there are no fixed points of F^k in this neighborhood, ie, the graph and the diagonal are disjoint over U. If there is an open set around $\Gamma_{F^k} \cap (U \times U)$ that misses the diagonal $\Delta \subset U \times U$, then any sufficiently small choice of X will keep Γ_{F^k} away from Δ and therefore produce no new closed orbits of the gradient flow. However, it may be that $\partial\Gamma_{F^k}$ has points on Δ. Indeed, if $c \subset \partial_+ W_\phi = \Sigma_{g+N}$ is the ascending slice of the critical point corresponding to $p = q$, suppose $h^k(c) \cap c \neq \emptyset$. Then it is not hard to see that $(p,p) \in \partial\Gamma_{F^k}$, and this situation cannot be eliminated by genericity assumptions on h. Essentially, p is both an ascending slice and a descending slice, so $\partial\Gamma_{F^k}$ can contain both $\{p\} \times (\text{asc.slice})$ and $(\text{desc.slice}) \times \{p\}$, and ascending and descending slices can have p as a boundary point.

Our perturbation of F using X amounts, over U, to a "vertical" isotopy of $\Gamma_{F^k} \subset U \times U$. The question of whether there is an X that produces no new fixed points is that of whether there is a vertical direction to move Γ_{F^k} that results in the "boundary-fixed" points like (p,p) described above remaining outside of $int(\Gamma_{F^k})$. The existence of such a direction is equivalent to the jump-discontinuity of F^k at p. This argument is easy to make formal in the case $k = 1$, and for $k > 1$ the ideas are the same, with some additional bookkeeping. We leave the general argument to the reader.

Turn now to the question of whether any new flow lines between critical points are created. Let $D = (h \circ F_1)^{-1}(\bigcup c_i)$ denote the first time that the descending manifolds of the critical points intersect Σ_g, and let $A = F_2 \circ h(\bigcup c_i)$ be the similar ascending slices. Then except for short flows, the flow lines between critical points are in 1–1 correspondence with intersections of D and $F^k(A)$, for various $k \geq 0$. We must show that our perturbations do not introduce new intersections between these sets. It is obvious from our constructions that only $F^k(A)$ is affected by the perturbation, since only F_2 is modified.

Since there are no short flows by assumption, there are no intersections of $h^{-1}(c_j)$ with c_i for any i and j. This means that D consists of a collection of embedded circles in Σ_g, where in general it may have included arcs connecting various q_i. Hence, we can choose our neighborhoods U_i small enough that $U_i \cap D = \emptyset$ for all i, and therefore the perturbed ascending slices $\tilde{F}^k(A)$ stay away from D. Hence no new flows between critical points are created.

This concludes the proof of Lemma 6.2. □

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