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# Knot invariants derived from the equivariant linking pairing

Christine Lescop

ABSTRACT. Let  $M$  be a closed oriented 3-manifold with first Betti number one. Its equivariant linking pairing may be seen as a two-dimensional cohomology class in an appropriate infinite cyclic covering of the configuration space of ordered pairs of distinct points of  $M$ . We show how to define the equivariant cube  $\mathcal{Q}(M, \mathbb{K})$  of this Blanchfield pairing with respect to a framed knot  $\mathbb{K}$  that generates  $H_1(M; \mathbb{Z})/\text{Torsion}$ .

We present the invariant  $\mathcal{Q}(M, \mathbb{K})$  and some of its properties including a surgery formula.

Via surgery, the invariant  $\mathcal{Q}$  is equivalent to an invariant  $\hat{\mathcal{Q}}$  of null-homologous knots in rational homology spheres, that is conjecturally equivalent to the two-loop part of the Kontsevich integral, that is often called the 2-loop polynomial.

We generalize the construction of  $\hat{\mathcal{Q}}$  to obtain a topological construction for an invariant that is conjecturally equivalent to the whole Kricker rational lift of the Kontsevich integral for null-homologous knots in rational homology spheres.

## 1. Introduction

**1.1. Background.** The study of 3-manifold invariants built from integrals over configuration spaces started after the work of Witten on Chern-Simons theory in 1989 [Wi], with work of Axelrod, Singer [AS1, AS2], Kontsevich [Ko], Bott, Cattaneo [BC1, BC2, C], Taubes [T]. In 1999, in [KT], G. Kuperberg and D. Thurston announced that some of these invariants, the Kontsevich ones, fit in with the framework of finite type invariants of homology spheres studied by Ohtsuki, Le, J. and H. Murakami, Goussarov, Habiro, Rozansky, Garoufalidis, Polyak, Bar-Natan [O, GGP, LMO, Å1, Å2, Å3] and others. They showed that these invariants together define a universal finite type invariant for homology 3-spheres. I gave specifications on the Kuperberg-Thurston work in [L1] and generalisations in [L2].

Similar studies for the knots and links cases had been performed by many other authors including Guadagnini, Martellini, Mintchev [GMM], Bar-Natan [B-N], Kontsevich [Ko2], Polyak, Viro [PV], Bott, Taubes [BT], Altschüler, Freidel [AF], D. Thurston [Th], Poirier [Po]. See also the Labastida survey [La] and the references therein.

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The above mentioned Kuperberg-Thurston work shows how to write the Casson invariant  $\lambda$ , originally defined by Casson in 1984 as an algebraic number of conjugacy classes of irreducible  $SU(2)$ -representations [AM, GM, M], as

$$\lambda(N) = \frac{1}{6} \int_{(N \setminus \{\infty\})^2 \setminus \text{diagonal}} \omega^3$$

for a homology sphere  $N$  (a closed oriented 3-manifold with the same integral homology as  $S^3$ ), a point  $\infty$  in  $N$ , and a closed 2-form  $\omega$  such that for any 2-component link

$$J \sqcup L: S^1 \sqcup S^1 \rightarrow N \setminus \{\infty\},$$

the linking number of  $J$  and  $L$  reads

$$lk(J, L) = \int_{J \times L} \omega.$$

In this sense,  $6\lambda(N)$  may be viewed as the *cube of the linking form of  $N$* . It can also be expressed as the algebraic triple intersection  $\langle F_X, F_Y, F_Z \rangle$  of three codimension 2 cycles  $F_X, F_Y, F_Z$  of  $(C_2(N), \partial C_2(N))$  (Poincaré dual to the previous  $\omega$ ) for a compactification  $C_2(N)$  of  $((N \setminus \{\infty\})^2 \setminus \text{diagonal})$  that is a 6-manifold with boundary. Here, for any 2-component link  $(J, L)$  of  $(N \setminus \{\infty\})$  as above, the linking number of  $J$  and  $L$  is the algebraic intersection of  $J \times L$  and  $F_X$ , (or  $F_Y$  or  $F_Z$ ) in the compactification  $C_2(N)$ . A complete definition of  $\lambda$  in these terms is described in the appendix.

**1.2. Introduction to the results.** In the first part of this article, we shall present a similar construction for an *equivariant cube  $\mathcal{Q}(M, \mathbb{K})$  of the equivariant linking pairing* for a closed 3-manifold  $M$  with  $H_1(M; \mathbb{Q}) = \mathbb{Q}$ , with respect to a framed knot  $\mathbb{K} = (K, K_{\parallel})$ , that is a knot  $K$  equipped with a parallel  $K_{\parallel}$ , such that  $H_1(M; \mathbb{Z})/\text{Torsion} = \mathbb{Z}[K]$ .

Our invariant will live in the field of rational functions  $\mathbb{Q}(x, y)$ . The simplest example of a pair  $(M, \mathbb{K})$  as above is the pair  $(S^1 \times S^2, S^1 \times u)$  where  $S^1 \times u$  is equipped with a parallel. Note that the choice of the parallel does not affect the diffeomorphism class of the pair  $(M, \mathbb{K})$  in this case. We shall have

$$\mathcal{Q}(S^1 \times S^2, S^1 \times u) = 0.$$

Furthermore, if  $N$  is a rational homology sphere, and if  $\sharp$  stands for the connected sum,

$$\mathcal{Q}(M \sharp N, \mathbb{K}) = \mathcal{Q}(M, \mathbb{K}) + 6\lambda(N)$$

where  $\lambda$  is the Walker generalization of the Casson invariant normalized like the Casson invariant in [AM, GM, M]. If  $\lambda_W$  denotes the Walker invariant normalized as in [W], then  $\lambda = \frac{\lambda_W}{2}$ .

We shall also state a surgery formula in Proposition 1.6 for our invariant, and we shall determine the vector space spanned by the differences  $(\mathcal{Q}(M, \mathbb{K}') - \mathcal{Q}(M, \mathbb{K}))$  for other framed knots  $\mathbb{K}'$  whose homology classes generate  $H_1(M; \mathbb{Z})/\text{Torsion}$ , in Proposition 1.8. This determination will allow us to define an induced invariant for closed oriented 3-manifolds with first Betti number one. This latter invariant should be equivalent to a special case

(the two-loop case) of invariants combinatorially defined by Ohtsuki in 2008, in [O3], for 3-manifolds of rank one.

Let  $M_{\mathbb{K}}$  be the manifold obtained from  $M$  by surgery on  $\mathbb{K}$ : This manifold is obtained from  $M$  by replacing a tubular neighborhood of  $K$  by another solid torus  $N(\hat{K})$  whose meridian is the given parallel  $K_{\parallel}$  of  $K$ . It is a rational homology sphere and the core  $\hat{K}$  of the new torus  $N(\hat{K})$  is a null-homologous knot in  $M_{\mathbb{K}}$ .

Our data  $(M, \mathbb{K})$  are equivalent to the data  $(M_{\mathbb{K}}, \hat{K})$ . Indeed,  $M$  is obtained from  $M_{\mathbb{K}}$  by 0-surgery on  $\hat{K}$ . Hence our invariant can be seen as an invariant of null-homologous knots in rational homology spheres. For these (and even for boundary links in rational homology spheres), following conjectures of Rozansky [Ro1], Garoufalidis and Kricker defined a rational lift of the Kontsevich integral in [Kr, GK], that generalizes the Rozansky 2-loop invariant of knots in  $S^3$  of [Ro1, Section 6, 6.9]. The two-loop part of this Kricker lift for knots is often called the two-loop polynomial. Its history and many of its properties are described in [O2]. Our invariant shares many features with this two-loop polynomial and is certainly *equivalent* to this invariant, in the sense that if one of the invariants distinguishes two knots with equivalent equivariant linking pairing, then the other one does. It should even be equal to the two-loop polynomial.

In 2005, Julien Marché also proposed a similar “cubic” definition of an invariant equivalent to the two-loop polynomial [Ma].

In terms of Jacobi diagrams or Feynman graphs, the Casson invariant was associated with the graph  $\theta$  and our equivariant cube is associated with the graph  $\theta$  with hair or beads.

All the results of the first part of this article are proved in [L3].

In the second part of this article, we explain how the topological construction of  $\mathcal{Q}(M, \mathbb{K})$  generalizes to the construction of an invariant of  $(M, \mathbb{K})$  that should be equivalent to the Kricker rational lift of the Kontsevich integral of null-homologous knots in rational homology spheres.

This article is an expansion of the talk I gave at the conference *Chern-Simons Gauge theory: 20 years after, Hausdorff center for Mathematics* in Bonn in August 2009. I thank the organizers Joergen Andersen, Hans Boden, Atle Hahn and Benjamin Himpel of this great conference.

The first part of the article and the appendix are of expository nature and do not contain all the proofs; that first part may be considered as a research announcement for the results of [L3]. The second part relies on some results of the first part and contains the construction of a more powerful invariant of  $(M, \mathbb{K})$  with the proof of its invariance.

I started to work on this project after a talk of Tomotada Ohtsuki for a workshop at the CTQM in Århus in Spring 2008. I wish to thank Joergen Andersen and Bob Penner for organizing this very stimulating meeting, and Tomotada Ohtsuki for discussing this topic with me.

**1.3. Conventions.** All the manifolds considered in this article are oriented. Boundaries are oriented by the *outward normal first* convention. The fiber  $N_u(A)$  of the normal bundle

$N(A)$  of an oriented submanifold  $A$  in an oriented manifold  $C$  at  $u \in A$  is oriented so that  $T_u C = N_u(A) \oplus T_u A$  as oriented vector spaces. For two oriented transverse submanifolds  $A$  and  $B$  of  $C$ ,  $A \cap B$  is oriented so that  $N_u(A \cap B) = N_u(A) \oplus N_u(B)$ . When the sum of the dimensions of  $A$  and  $B$  is the dimension of  $C$ , and when  $A \cap B$  is finite, the *algebraic intersection*  $\langle A, B \rangle$  of  $A$  and  $B$  in  $C$  is the sum of the signs of the points of  $A \cap B$ , where the sign of an intersection point  $u$  of  $A \cap B$  is 1 if and only if  $T_u C = N_u(A) \oplus N_u(B)$  (that is if and only if  $T_u C = T_u A \oplus T_u B$ ) as oriented vector spaces. It is  $(-1)$  otherwise. The algebraic intersection of  $n$  compact transverse submanifolds  $A_1, A_2, \dots, A_n$  of  $C$  whose codimensions sum is the dimension of  $C$  is defined similarly. The sign of an intersection point  $u$  is 1 if and only if  $T_u C = N_u(A_1) \oplus N_u(A_2) \oplus \dots \oplus N_u(A_n)$  as oriented vector spaces.

**1.4. On the equivariant linking pairing.** Fix  $(M, \mathbb{K})$  as in Subsection 1.2. Let

$$q: \tilde{M} \rightarrow M$$

denote the regular infinite cyclic covering of  $M$ , and let  $\theta_M$  be the generator of its covering group that corresponds to the action of the class of  $K$ . The action of  $\theta_M$  on  $H_1(\tilde{M}; \mathbb{Q})$  is denoted as the multiplication by  $t_M$ .

The  $\mathbb{Q}[t_M^{\pm 1}]$ -module  $H_1(\tilde{M}; \mathbb{Q})$  reads

$$H_1(\tilde{M}; \mathbb{Q}) = \bigoplus_{i=1}^k \frac{\mathbb{Q}[t_M^{\pm 1}]}{\delta_i}$$

for polynomials  $\delta_i$  of  $\mathbb{Q}[t_M^{\pm 1}]$  where  $\delta_i$  divides  $\delta_{i+1}$ . Then  $\delta = \delta(M) = \delta_k$  is the *annihilator* of  $H_1(\tilde{M}; \mathbb{Q})$  and  $\Delta = \Delta(M) = \prod_{i=1}^k \delta_i$  is the *Alexander polynomial* of  $M$ .

These very classical invariants are normalised so that  $\Delta(t_M) = \Delta(t_M^{-1})$ ,  $\Delta(1) = 1$ ,  $\delta(t_M) = \delta(t_M^{-1})$  and  $\delta(1) = 1$ . (In order to make  $\delta$  symmetric, we may have to allow it to belong to  $(t_M^{1/2} + t_M^{-1/2})\mathbb{Q}[t_M^{\pm 1}] \cup \mathbb{Q}[t_M^{\pm 1}]$ .) Note that  $\Delta$  and  $\delta$  coincide when  $\Delta$  has no multiple roots.

Let  $(J, L)$  be a two-component link of  $\tilde{M}$  such that  $q(J) \cap q(L) = \emptyset$ . If  $J$  bounds a (compact) surface  $\Sigma$  in  $\tilde{M}$  transverse to  $\theta_M^n(L)$  for all  $n$ , define the *equivariant intersection*  $\langle \Sigma, L \rangle_e$  as

$$\langle \Sigma, L \rangle_e = \sum_{n \in \mathbb{Z}} t_M^n \langle \Sigma, \theta_M^n(L) \rangle$$

where  $\langle \Sigma, \theta_M^n(L) \rangle$  is the usual algebraic intersection. Then the *equivariant linking pairing* of  $J$  and  $L$  is

$$lk_e(J, L) = \langle \Sigma, L \rangle_e.$$

In general,  $\delta(\theta_M)(J)$  bounds a surface  $\delta(\theta_M)\Sigma$  and

$$lk_e(J, L) = \frac{\langle \delta(\theta_M)\Sigma, L \rangle_e}{\delta(t_M)}.$$

For any two one-variable polynomials  $P$  and  $Q$ ,

$$lk_e(P(\theta_M)(J), Q(\theta_M)(L)) = P(t_M)Q(t_M^{-1})lk_e(J, L).$$

**1.5. The construction of  $\mathcal{Q}(M, \mathbb{K})$ .** Consider the infinite cyclic covering of  $M^2$

$$\widetilde{M^2} = \frac{\widetilde{M^2}}{(u, v) \sim (\theta_M(u), \theta_M(v))} \xrightarrow{q_2} M^2$$

with generating covering transformation  $\theta$ .

$$\theta(\overline{(u, v)}) = \overline{(\theta_M(u), v)} = \overline{(u, \theta_M^{-1}(v))}.$$

The diagonal of  $(\widetilde{M^2})$  projects to a preferred lift of the diagonal of  $M^2$  in  $\widetilde{M^2}$ .

$$q_2^{-1}(\text{diag}(M^2)) = \sqcup_{n \in \mathbb{Z}} \theta^n \left( \overline{\text{diag}(\widetilde{M^2})} = \text{diag}(M^2) \right) = \mathbb{Z} \times \text{diag}(M^2).$$

**Definition 1.1.** In a smooth  $n$ -manifold  $C$ , a tubular neighborhood of a compact  $m$ -submanifold  $A$  locally reads as  $\mathbb{R}^{n-m} \times U$  for some open  $U \subset A$ , where

$$\mathbb{R}^{n-m} = (]0, \infty[ \times S^{n-m-1}) \cup \{0\}$$

stands for the fiber of the normal bundle of  $A$ , and  $S^{n-m-1}$  stands for the fiber of the unit normal bundle of  $A$ . In this article, the manifold  $C(A)$  obtained by *blowing-up*  $A$  in  $C$  is obtained by replacing  $A$  by its unit normal bundle in  $A$ . Near  $U$ ,  $\mathbb{R}^{n-m} \times U$  is replaced by  $]0, \infty[ \times S^{n-m-1} \times U$ . The blown-up manifold  $C(A)$  is homeomorphic to the complement of an open tubular neighborhood of  $A$  in  $C$ , but it has a canonical smooth projection onto  $C$  and a canonical smooth structure. When  $C$  and  $A$  are compact,  $C(A)$  is a compactification of  $C \setminus A$ .

Our *configuration space*  $\widetilde{C}_2(M)$  is obtained from  $\widetilde{M^2}$  by blowing up  $q_2^{-1}(\text{diag}(M^2))$  in this sense. The transformation  $\theta$  of  $\widetilde{M^2}$  naturally lifts to a transformation of  $\widetilde{C}_2(M)$  that is still denoted by  $\theta$ .

Since the normal bundle of the diagonal is canonically equivalent to the tangent bundle  $TM$  of  $M$  via

$$(u, v) \in \frac{TM^2}{\text{diag}(TM^2)} \mapsto (v - u) \in TM,$$

the unit normal bundle of  $q_2^{-1}(\text{diag}(M^2))$  is  $\mathbb{Z} \times ST(M)$  where  $ST(M)$  is the unit tangent bundle of  $M$  so that

$$\partial \widetilde{C}_2(M) = \mathbb{Z} \times ST(M).$$

A trivialisation  $\tau : TM \rightarrow M \times \mathbb{R}^3$  of  $TM$  identifies  $ST(M)$  to  $M \times S^2$ .

Like any oriented closed 3-manifold,  $M$  bounds an (oriented compact) 4-dimensional manifold  $W^4$  with signature 0. Then  $TW^4|_M = \mathbb{R} \oplus TM$ . A trivialisation  $\tau$  of  $TM$  induces a trivialisation of  $TW^4 \otimes \mathbb{C}$  on  $M$ . The *first Pontrjagin class*  $p_1(\tau)$  of such a trivialisation  $\tau$  of the tangent bundle of  $M$  is the obstruction  $p_1(W^4; \tau)$  to extend this trivialisation to  $W^4$ . It belongs to  $H^4(W^4, M; \pi_3(SU(4))) = \mathbb{Z}$ . We use the notation and conventions of [MS], see also [L1, Section 1.5].

Now, the construction of  $\mathcal{Q}(M, \mathbb{K})$  is given by the following theorem.

**Theorem 1.2.** *Let  $\tau : TM \rightarrow M \times \mathbb{R}^3$  be a trivialisation of  $TM$  and let  $p_1(\tau)$  be its first Pontrjagin class. Assume that  $\tau$  maps the oriented unit tangent vectors of  $K$  to some fixed  $W \in S^2$ . Then  $\tau$  induces a parallelisation of  $K$ . Let  $K_X, K_Y, K_Z$  be three disjoint parallels of  $K$ , on the boundary  $\partial N(K)$  of a tubular neighborhood of  $K$ , that induce the same parallelisation of  $K$  as  $\tau$ .*

Consider the continuous map

$$\begin{aligned} \check{A}(K): \quad (S^1 = [0, 1]/(0 \sim 1)) \times [0, 1] &\rightarrow C_2(M) \\ (t, u \in ]0, 1[) &\mapsto (K(t), K(t+u)), \end{aligned}$$

and its lift  $A(K): S^1 \times [0, 1] \rightarrow \tilde{C}_2(M)$  such that the lift of  $(K(t), K(t+\varepsilon))$  is in a small neighborhood of the canonical lift of the diagonal, for a small positive  $\varepsilon$ . Let  $A(K)$  also denote the 2-chain  $A(K)(S^1 \times [0, 1])$ .

For  $V \in S^2$ , let

$$s_\tau(M; V) = \tau^{-1}(M \times V) \subset ST(M) = \{0\} \times ST(M) \subset \partial \tilde{C}_2(M).$$

Let

$$I_\Delta(t) = \frac{1+t}{1-t} + \frac{t\Delta'(t)}{\Delta(t)}$$

where  $\Delta = \Delta(M)$ . Let  $X, Y, Z$  be three distinct points in  $S^2 \setminus \{W, -W\}$ .

There exist three rational 4-dimensional chains  $G_X, G_Y$  and  $G_Z$  of  $\tilde{C}_2(M)$  whose boundaries are

$$\begin{aligned} \partial G_X &= (\theta - 1)\delta(\theta) (s_\tau(M; X) - I_\Delta(\theta)ST(M)|_{K_X}), \\ \partial G_Y &= (\theta - 1)\delta(\theta) (s_\tau(M; Y) - I_\Delta(\theta)ST(M)|_{K_Y}) \text{ and} \\ \partial G_Z &= (\theta - 1)\delta(\theta) (s_\tau(M; Z) - I_\Delta(\theta)ST(M)|_{K_Z}) \end{aligned}$$

and such that the following equivariant algebraic intersections in  $\tilde{C}_2(M)$  vanish

$$\langle G_X, A(K) \rangle_e = \langle G_Y, A(K) \rangle_e = \langle G_Z, A(K) \rangle_e = 0.$$

Define the equivariant algebraic triple intersection in  $\tilde{C}_2(M)$

$$\langle G_X, G_Y, G_Z \rangle_e = \sum_{(i,j) \in \mathbb{Z}^2} \langle G_X, \theta^{-i}(G_Y), \theta^{-j}G_Z \rangle_{\tilde{C}_2(M)} y^i z^j \in \mathbb{Q}[y^{\pm 1}, z^{\pm 1}].$$

Let  $R_\delta = \frac{\mathbb{Q}[x^{\pm 1}, y^{\pm 1}, z^{\pm 1}, \frac{1}{\delta(x)}, \frac{1}{\delta(y)}, \frac{1}{\delta(z)}]}{(xyz=1)}$ . Then

$$\mathcal{Q}(M, \mathbb{K}) = \frac{\langle G_X, G_Y, G_Z \rangle_e}{(x-1)(y-1)(z-1)\delta(x)\delta(y)\delta(z)} - \frac{p_1(\tau)}{4} \in R_\delta$$

only depends on the isotopy class of the knot  $K$  and on its parallelisation. Furthermore,

$$\delta(x)\delta(y)\delta(z)\mathcal{Q}(M, \mathbb{K}) \in \frac{\mathbb{Q}[x^{\pm 1}, y^{\pm 1}, z^{\pm 1}]}{(xyz=1)},$$

$\mathcal{Q}(M, \mathbb{K})(x, y, z) = \mathcal{Q}(M, \mathbb{K})(y, x, z) = \mathcal{Q}(M, \mathbb{K})(z, y, x) = \mathcal{Q}(M, \mathbb{K})(x^{-1}, y^{-1}, z^{-1})$  and  $\mathcal{Q}(M, \mathbb{K})$  does not depend on the orientation of  $K$ .

Of course, the theorem above contains a lot of statements. Let us explain their flavour. Consider the homology of  $\tilde{C}_2(M)$  with coefficients in  $\mathbb{Q}$  endowed with the structure of  $\mathbb{Q}[t, t^{-1}]$ -module where the multiplication by  $t$  is induced by the action of  $\theta$  on  $\tilde{C}_2(M)$ . Let  $\mathbb{Q}(t)$  be the field of fractions of  $\mathbb{Q}[t, t^{-1}]$  and set

$$H_*(C_2(M); \mathbb{Q}(t)) = H_*(\tilde{C}_2(M); \mathbb{Q}) \otimes_{\mathbb{Q}[t, t^{-1}]} \mathbb{Q}(t).$$

**Lemma 1.3.**  $H_i(C_2(M); \mathbb{Q}(t)) = H_{i-2}(M; \mathbb{Q}) \otimes_{\mathbb{Q}} \mathbb{Q}(t)$  for any  $i \in \mathbb{Z}$ .

$$H_2(C_2(M); \mathbb{Q}(t)) = \mathbb{Q}(t)[ST(M)_{|*} (\cong * \times S^2)]$$

$$H_3(C_2(M); \mathbb{Q}(t)) = \mathbb{Q}(t)[ST(M)_{|K} (\cong K \times S^2)]$$

$$H_4(C_2(M); \mathbb{Q}(t)) = \mathbb{Q}(t)[ST(M)_{|S} (\cong S \times S^2)]$$

where  $S$  is a closed surface of  $M$  such that  $H_2(M; \mathbb{Z}) = \mathbb{Z}[S]$ .

In particular, the statement of the theorem contains the following lemma:

**Lemma 1.4.** *The homology class in  $H_3(C_2(M); \mathbb{Q}(t))$  of a global section of  $ST(M)$  induced by a trivialisation of  $M$  is  $I_{\Delta}[ST(M)_{|K}]$ .*

Therefore, this  $I_{\Delta}[ST(M)_{|K}]$  cannot be removed from our boundaries. Lemma 1.3 can be proved by classical means. Observe that since

$$\langle A(K), ST(M)_{|S} \rangle_e = 1 - t^{-1},$$

the class of  $A(K)$  in  $H_2(\tilde{C}_2(M), \partial\tilde{C}_2(M))$  detects  $[ST(M)_{|S}]$ . Thus, the condition  $\langle A(K), G_X \rangle_e = 0$  ensures that if  $G'_X$  satisfies the same conditions as  $G_X$ ,  $(G'_X - G_X)$  bounds a 5-chain and  $\langle G'_X, G_Y, G_Z \rangle_e = \langle G_X, G_Y, G_Z \rangle_e$ . Therefore, our algebraic intersection  $\langle G_X, G_Y, G_Z \rangle_e$  is well-defined.

The class of  $F_X = \frac{G_X}{(t-1)\delta(t)}$  (that is the same as the class of  $F_Y = \frac{G_Y}{(t-1)\delta(t)}$  or  $F_Z = \frac{G_Z}{(t-1)\delta(t)}$ ) in  $H_4(C_2(M), \partial C_2(M); \mathbb{Q}(t))$  is dual to  $[ST(M)_{|*}]$ :

$$\langle ST(M)_{|*}, F_X \rangle_e = 1.$$

For a two-component link  $(J, L)$  of  $\tilde{M}$  such that  $q(J) \cap q(L) = \emptyset$ , the class of  $J \times L$  in  $\tilde{C}_2(M)$  reads  $lk_e(J, L)[ST(M)_{|*}]$ . By the above equation, this can be rewritten as

$$lk_e(J, L) = \langle J \times L, F_X \rangle_e$$

and the chains  $F_V$  represent the equivariant linking number in this sense.

Recall that all the assertions of this section are proved in details in [L3].

**1.6. A few properties of  $\mathcal{Q}$ .** Recall that  $\lambda$  denotes the Casson-Walker invariant normalised like the Casson invariant. I added the following proposition in order to answer a question that George Thompson asked me at the conference *Chern-Simons Gauge theory : 20 years after* in Bonn. I thank him for asking.

**Proposition 1.5.** *Let  $M_{\mathbb{K}}$  denote the rational homology sphere obtained from  $M$  by surgery along  $\mathbb{K}$ . Then*

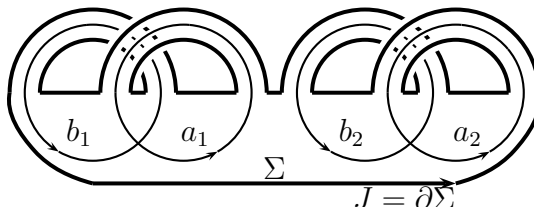
$$\mathcal{Q}(M, \mathbb{K})(1, 1, 1) = 6\lambda(M_{\mathbb{K}}).$$



For a function  $f$  of  $x$  and  $y$ ,  $\sum_{\mathfrak{S}_3(x,y,z)} f(x,y)$  stands for  $\sum_{\sigma \in \mathfrak{S}_3(x,y,z)} f(\sigma(x), \sigma(y))$  where  $\mathfrak{S}_3(x,y,z)$  is the set of permutations of  $\{x,y,z\}$ .

**Proposition 1.6.** *Let  $J$  be a knot of  $M$  that bounds a Seifert surface  $\Sigma$  disjoint from  $K$  whose  $H_1$  goes to 0 in  $H_1(M)/\text{Torsion}$ .*

*Let  $p/q$  be a nonzero rational number. Let  $(a_i, b_i)_{i=1,\dots,g}$  be a symplectic basis of  $H_1(\Sigma)$ .*



Let

$$\lambda'_e(J) = \frac{1}{12} \sum_{(i,j) \in \{1,\dots,g\}^2} \sum_{\mathfrak{S}_3(x,y,z)} (\alpha_{ij}(x,y) + \alpha_{ij}(x^{-1}, y^{-1}) + \beta_{ij}(x,y)) \in R_\delta$$

where

$$\alpha_{ij}(x,y) = lk_e(a_i, a_j^+)(x) lk_e(b_i, b_j^+)(y) - lk_e(a_i, b_j^+)(x) lk_e(b_i, a_j^+)(y)$$

and

$$\beta_{ij}(x,y) = (lk_e(a_i, b_i^+)(x) - lk_e(b_i^+, a_i)(x)) (lk_e(a_j, b_j^+)(y) - lk_e(b_j^+, a_j)(y)),$$

then

$$\mathcal{Q}(M(J; p/q), \mathbb{K}) - \mathcal{Q}(M, \mathbb{K}) = 6 \frac{q}{p} \lambda'_e(J) + 6\lambda(S^3(U; p/q))$$

where  $S^3(U; p/q)$  is the lens space  $L(p, -q)$  obtained from  $S^3$  by  $p/q$ -surgery on the unknot  $U$ .

Since  $H_1(\Sigma)$  goes to 0 in  $H_1(M)/\text{Torsion}$  in the above statement,  $\Sigma$  lifts as homeomorphic copies of  $\Sigma$  and  $lk_e(a_i, a_j^+)$  denotes the equivariant linking number of a lift of  $a_i$  in  $\tilde{M}$  in some lift of  $\Sigma$  and a lift of  $a_j^+$  near the same lift of  $\Sigma$ . The superscript  $+$  means that  $a_j$  is pushed in the direction of the positive normal to  $\Sigma$ .

In [L3], we deduce the surgery formula of Proposition 1.6 for surgeries on knots from a surgery formula for lagrangian-preserving replacements of rational homology handlebodies.

When the above knot  $J$  is inside a rational homology ball,  $\lambda'_e(J)$  coincides with  $\frac{1}{2}\Delta''(J)$ , where  $\Delta(J)$  is the Alexander polynomial of  $J$ , and the right-hand side is nothing but 6 times the variation of the Casson-Walker invariant under a  $p/q$ -surgery on  $J$ . Since any rational homology sphere can be obtained from  $S^3$  by a sequence of surgeries on null-homologous knots in rational homology spheres with nonzero coefficients, after a possible connected sum with lens spaces, we easily deduce the following proposition from the above surgery formula.

**Proposition 1.7.** *Let  $N$  be a rational homology sphere, then*

$$\mathcal{Q}(M\sharp N, \mathbb{K}) = \mathcal{Q}(M, \mathbb{K}) + 6\lambda(N).$$

$$\text{Recall } I_\Delta(t) = \frac{1+t}{1-t} + \frac{t\Delta'(t)}{\Delta(t)}.$$

**Proposition 1.8.** *Let  $\mathbb{K}'$  be another framed knot of  $M$  such that  $H_1(M)/\text{Torsion} = \mathbb{Z}[K']$ . Then there exists an antisymmetric polynomial  $\mathcal{V}(\mathbb{K}, \mathbb{K}')$  in  $\mathbb{Q}[t, t^{-1}]$  such that*

$$\mathcal{Q}(M, \mathbb{K}') - \mathcal{Q}(M, \mathbb{K}) = \sum_{\mathfrak{S}_3(x, y, z)} \frac{\mathcal{V}(\mathbb{K}, \mathbb{K}')(x)}{\delta(x)} I_\Delta(y).$$

Furthermore, for any  $k \in \mathbb{Z}$ , there exists a pair of framed knots  $(\mathbb{K}, \mathbb{K}')$  such that  $\mathcal{V}(\mathbb{K}, \mathbb{K}') = q(t^k - t^{-k})$  for some nonzero rational number  $q$ .

**Proposition 1.9.** *If  $\mathbb{K} = (K, K_\parallel)$  and if  $\mathbb{K}' = (K, K'_\parallel)$ , where  $K'_\parallel$  is another parallel of  $K$  such that the difference  $(K'_\parallel - K_\parallel)$  is homologous to a positive meridian of  $K$  in  $\partial N(K)$ , then*

$$\mathcal{V}(\mathbb{K}, \mathbb{K}')(t) = -\frac{\delta(t) t \Delta'(t)}{2 \Delta(t)}.$$

**Proposition 1.10.** *If  $K$  and  $K'$  coincide along an interval, if  $K' - K$  bounds a surface  $B$  that lifts in  $\tilde{M}$  such that  $(K'_\parallel - K_\parallel)$  is homologous to a curve of  $B$  in the complement of  $(\partial B \cup K)$  in a regular neighborhood of  $B$ , and if  $(a_i, b_i)_{i \in \{1, \dots, g\}}$  is a symplectic basis of  $H_1(B; \mathbb{Z})$ , then*

$$\frac{\mathcal{V}(\mathbb{K}, \mathbb{K}')(t)}{\delta(t)} = \sum_{i=1}^g \left( lk_e(a_i, b_i^+) - \overline{lk_e(a_i, b_i^+)} \right).$$

### 1.7. The derived 3-manifold invariant.

**Definition 1.11.** *Definition of an invariant for 3-manifolds of rank one:*

Let  $Q_k(\delta, \Delta) = \sum_{\mathfrak{S}_3(x, y, z)} \frac{x^k - x^{-k}}{\delta(x)} I_\Delta(y)$  for  $k \in (\mathbb{N} \setminus \{0\})$ . For a fixed  $(\delta, \Delta)$ , define  $\mathcal{Q}(M)$  in the quotient of  $R_\delta$  by the vector space generated by the  $Q_k(\delta, \Delta)$  for  $k \in (\mathbb{N} \setminus \{0\})$  as the class of  $\mathcal{Q}(M, \mathbb{K})$ .

Thanks to Proposition 1.8,  $\mathcal{Q}(M)$  is an invariant of  $M$ . This invariant is certainly equivalent to a special case (the two-loop case) of invariants combinatorially defined by Ohtsuki in 2008 in [O3], for 3-manifolds of rank one, when  $\delta = \Delta$ . The following proposition shows that it often detects the connected sums with rational homology spheres with non-trivial Casson-Walker invariants.

**Proposition 1.12.** *If  $\Delta$  has only simple roots, if  $N$  is a rational homology sphere such that  $\lambda(N) \neq 0$ , then  $\mathcal{Q}(M) \neq \mathcal{Q}(M \sharp N)$ .*

## 2. Construction of more general invariants

The invariant that has been discussed so far corresponds to the graph  $\theta$  (with hair or beads), where the two vertices of the graph  $\theta$  correspond to the two points of a configuration in  $C_2(M)$ , and the three edges are equipped with  $F_X$ ,  $F_Y$ , and  $F_Z$ , respectively.

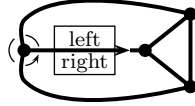
The chains  $F_V$  that were used in the definition of  $\mathcal{Q}$  can be used to define invariants  $\tilde{z}_n(M, \mathbb{K})$  of  $(M, \mathbb{K})$  associated to beaded trivalent graphs with  $2n$  vertices, and thus to configuration spaces  $C_{2n}(M)$  of  $2n$  points. We present the construction of these invariants

below. Together, they will form a series  $(\tilde{z}_n(M, \mathbb{K}))_{n \in \mathbb{N}}$ , that should be equivalent to the Kricker rational lift of the Kontsevich integral for null-homologous knots in rational homology spheres, described in [Kr, GK].

**2.1. On the target spaces.** Here, a *trivalent graph* is a finite trivalent graph

- without loops (edges whose two ends coincide),
- each edge of which has two sides, that are respectively called left and right when the edge is equipped with an orientation, so that reversing the edge orientation reverses the left and right notion.

Such a graph will be said to be *oriented* if each of its vertices is equipped with a *vertex orientation*, that is a cyclic order of the three edges that meet at this vertex. Such an oriented graph will be represented by the image of one of its planar immersions so that the vertex orientation is induced by the counterclockwise order of the edges meeting at this vertex, and the two sides of an edge are the two sections of the unit normal bundle of the immersion of this edge.



Let  $\mathcal{A}_n^h$  be the rational vector space generated by oriented trivalent graphs with  $2n$  vertices whose edges are equipped with some rational functions of  $\mathbb{Q}(t)$  on one side of each edge, and quotiented by the following relations:

- (1) Putting  $P(t)$  on one side of an edge or putting  $P(t^{-1})$  on the other side gives the same element in the quotient.

$$\begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{P(t)} \end{array} = \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{P(t^{-1})} \end{array}$$

- (2) If two graphs only differ by the label of one edge, that is  $P(t)$  for one of them and  $Q(t)$  for the other one (on the same side), then the class of their sum is the class of the same graph with label  $(P(t) + Q(t))$ .

$$\begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{P(t) + Q(t)} \end{array} = \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{P(t)} \end{array} + \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{Q(t)} \end{array}$$

- (3) Multiplying by  $t$  the three rational functions on the left sides of the edges adjacent to a vertex, oriented towards that vertex, does not change the element in the quotient.

$$\begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{P(t)} \end{array} \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{R(t)} \end{array} \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{Q(t)} \end{array} = \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{tP(t)} \end{array} \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{tR(t)} \end{array} \begin{array}{c} \text{---} \\ \diagup \quad \diagdown \\ \text{---} \\ \boxed{tQ(t)} \end{array}$$

- (4) (AS) Changing the orientation of a vertex multiplies the element of the quotient by  $(-1)$ .

$$\begin{array}{c} \diagup \\ \text{---} \\ \diagdown \end{array} + \begin{array}{c} \diagdown \\ \text{---} \\ \diagup \end{array} = 0$$

- (5) (IHX) The sum of three graphs that coincide outside a disk, where they look as in the picture below, vanishes in the quotient. (The complete edges of the relation are equipped with the polynomial 1 that is not written.)

$$\begin{array}{c} \diagup \\ \diagdown \end{array} + \begin{array}{c} \diagdown \\ \diagup \end{array} + \begin{array}{c} \text{---} \\ \diagup \\ \diagdown \end{array} = 0 \quad \text{where} \quad \begin{array}{c} \text{---} \\ \diagup \\ \diagdown \end{array} = \begin{array}{c} \diagup \\ \text{---} \\ \diagdown \end{array}.$$

For example, there is an injection

$$\psi: \mathcal{A}_1^h \rightarrow \mathbb{Q}(x, y)$$

that maps the graph  $\theta$  with  $t^a$  above its upper edge,  $t^b$  above the middle one and  $t^c$  above the lower edge to the polynomial  $\sum_{\mathfrak{S}_3(x,y,z)} (x^a y^b z^c + x^{-a} y^{-b} z^{-c})$  where  $z = (xy)^{-1}$ .

A more general version of this space of diagrams was introduced in [GK, Definition 3.8].

**2.2. On compactifications of configuration spaces.** We describe the main features of the Fulton and MacPherson compactifications of configuration spaces [FMcP] that are used to define configuration space invariants of knots or manifolds. Details can be found in [L1, Section 3].

Let  $N$  be a finite set, and let  $I$  be a subset of  $N$  with cardinality  $\#I$  greater than 1. Let  $\Delta_I(M^N) = \{(m_i)_{i \in N}; m_i = m_j \text{ if } \{i, j\} \subset I\}$ .  $\Delta_I(M^N)$  is a codimension  $3(\#I - 1)$ -manifold. The fiber of its unit normal bundle at  $(m_j)_{j \in N}$  is the space  $(T_{m_i} M^I / \Delta_I(T_{m_i} M^I) \setminus \{0\}) / \mathbb{R}^{+*}$  where  $i \in I$ . It is the space  $C_I(T_{m_i} M)$  of  $I$ -tuples of points of the tangent space  $T_{m_i} M$  up to global translation and global homothety with positive ratio. Thus, in the blown-up manifold  $M^N(\Delta_I(M^N))$  (see Definition 1.1), a point  $P$  that projects to  $\Delta_I(M^N)$  under the canonical projection is equipped with the data of the infinitely small configuration  $c_I(P) \in C_I(T_{m_i} M)$  of the points  $m_i$  indexed by  $I$  in  $T_{m_i} M$  (up to translation and dilation).

Of course, the manifold  $C_2(M)$  reads  $M^2(\Delta_{\{1,2\}}(M^2))$  with this notation.

Let  $J$  be a subset of  $I$ ,  $J \subsetneq I$ ,  $\#J \geq 2$ .

$$\Delta_I(M^N) \subset \Delta_J(M^N)$$

The closure of  $\Delta_J(M^N) \setminus \Delta_I(M^N)$  in  $M^N(\Delta_I(M^N))$  is the submanifold  $\Delta_J(M^N)(\Delta_I(M^N))$ , and we can blow-up  $M^N(\Delta_I(M^N))$  along  $\Delta_J(M^N)(\Delta_I(M^N))$  to get a manifold with boundary and with corners, where the relative configuration of the possibly coinciding points of  $T_{m_i} M$  indexed by elements of  $J$  in an infinitely small configuration of points  $c_I(P)$  of  $T_{m_i} M$  is known. It is thought of as infinitely smaller.

**Definition 2.1.** Let  $\Gamma$  be a graph whose vertices are indexed by  $\{1, 2, \dots, 2n\}$ . When  $I$  is a subset of  $\{1, 2, \dots, 2n\}$ , the graph  $\Gamma_I$  is the subgraph of  $\Gamma$  made of the vertices indexed in  $I$  and the edges between two of them. The *configuration space*  $C_{2n}(M, \Gamma)$  is

the smooth compact  $6n$ -manifold with corners obtained by blowing-up successively all the  $\Delta_I(M^N)$  for which  $\Gamma_I$  is connected, inductively, starting with maximal not yet treated  $I$  with this property. The space  $C_{2n}(M, \Gamma)$  is a compactification of the complement of all the diagonals of  $M^{2n}$  that projects to  $M^{2n}$ , canonically. The *configuration space*  $C_{2n}(M)$  is  $C_{2n}(M, \Gamma_c)$  where  $\Gamma_c$  is the complete graph with  $2n$  vertices.

Let  $P_0$  be a point of  $C_{2n}(M, \Gamma)$ , it projects to  $(m_i)_{i \in \{1, 2, \dots, 2n\}}$ . Consider the maximal connected subgraphs  $\Gamma_I$  of  $\Gamma$  (with  $\sharp I \geq 2$ ) such that  $m_j = m_k$  whenever  $j$  and  $k$  are in  $I$ . For each of these subgraphs  $\Gamma_I$ , consider the maximal connected subgraphs  $\Gamma_J$  with  $\sharp J \geq 2$  and  $J \subsetneq I$  such that the points indexed by  $J$  coincide in the infinitely small configuration  $c_I(P_0)$ . Iterating the process, the “considered” graphs form a family  $\mathcal{E}(P_0)$  of connected subgraphs  $\Gamma_I$  of  $\Gamma$  such that the intersection  $\Gamma_I \cap \Gamma_J$  of any two graphs of the family is  $\Gamma_I$ ,  $\Gamma_J$  or  $\emptyset$ . The points  $P$  such that  $\mathcal{E}(P)$  is empty are the points in the interior of  $C_{2n}(M, \Gamma)$ . If  $\mathcal{E}(P_0) \neq \emptyset$ , the points  $P$  such that  $\mathcal{E}(P) = \mathcal{E}(P_0)$  are in the boundary of  $C_{2n}(M, \Gamma)$  and they form a codimension  $\sharp \mathcal{E}(P_0)$  *face* of  $C_{2n}(M, \Gamma)$ . In particular, the *codimension 1 faces* of  $\partial C_{2n}(M, \Gamma)$  correspond to connected subgraphs  $\Gamma_I$  of  $\Gamma$ .

For every oriented edge  $e$  of  $\Gamma$  from the vertex  $v(j)$  of  $\Gamma$  indexed by  $j$  to  $v(k)$ , there is a canonical projection

$$p(\Gamma, e): C_{2n}(M, \Gamma) \rightarrow C_2(M)$$

that maps a point  $P$  that projects to  $(m_i)_{i \in \{1, 2, \dots, 2n\}}$  to  $(m_j, m_k)$  if  $m_j \neq m_k$ , and to the infinitely small configuration of  $(T_{m_j} M^{\{j, k\}} / \Delta_{\{j, k\}}(T_{m_j} M^{\{j, k\}}) \setminus \{0\}) / \mathbb{R}^{+*}$  that can be seen at some scale in  $C_{2n}(M, \Gamma)$ , if  $m_j = m_k$ .

**2.3. Definition of the invariants  $\tilde{z}_n(M, \mathbb{K})$ .** Fix  $(M, \mathbb{K}, \tau)$  as in the first part. Recall that  $\tau$  maps the tangent vectors of  $K$  to  $\mathbb{R}W$ , for some  $W \in S^2$ . For any  $n \in \mathbb{N} \setminus \{0\}$ , the invariant  $\tilde{z}_n(M, \mathbb{K}, \tau)$  is defined as follows. Consider

- a *regular*  $3n$ -tuple  $(X_1, \dots, X_{3n})$  of  $(S^2 \setminus \{W, -W\})^{3n}$ , where *regular* means in some open dense subset of  $(S^2 \setminus \{W, -W\})^{3n}$  that will be specified in Subsection 2.4,
- $3n$  disjoint parallels  $(K_1, \dots, K_{3n})$  of  $K$  on  $\partial N(K)$ , with respect to the parallelisation of  $\mathbb{K}$ ,
- $3n$  integral chains (integral combinations of properly  $C^\infty$ -embedded 4-simplices)  $H_i$  in *general  $3n$ -position* in  $\tilde{C}_2(M)$ 
  - whose boundaries are

$$k(t-1)\delta(t)(s_\tau(M; X_i) - I_\Delta(t)ST(M)|_{K_i}),$$

respectively, for some positive integer  $k$ ,

- and such that  $\langle H_i, A(K) \rangle_e = 0$ .

The notion of *general  $3n$ -position* will be specified in Definition 2.2.

The chains  $H_i$  will be seen as cycles of  $(C_2(M), \partial C_2(M))$  (combinations of simplices) with coefficients in  $\mathbb{Q}[H_1(M)/\text{Torsion}]$  by projection as follows. Pick a basepoint  $*$  in  $\tilde{C}_2(M)$ , and consider the equivalence relation on the set of paths from the projection  $p(*)$  of  $*$  in  $C_2(M)$  to some other point in  $C_2(M)$  that identifies two paths if they lift to paths with identical ends

in  $\tilde{C}_2(M)$ . For a point of  $C_2(M)$  that projects to  $(m_1, m_2) \in M^2$ , this datum is equivalent to a rational homology class of paths from  $m_1$  to  $m_2$ . A *chain of*  $(C_2(M), \partial C_2(M))$  with *coefficients* in  $\mathbb{Q}[H_1(M)/\text{Torsion}]$  is a chain every point  $P$  of which is equipped with a class of paths from  $p(*)$  to  $P$  as above, in a continuous way (or every simplex (or contractible cell) of which is equipped with such a class of paths in a way compatible with face identifications).

Let  $\mathcal{S}_n$  be the set of connected trivalent graphs  $\Gamma$  with  $2n$  vertices numbered from 1 to  $2n$  and with oriented edges numbered from 1 to  $3n$  without loops.

Consider  $\Gamma \in \mathcal{S}_n$ . Let  $C_{2n}(M, \Gamma)$  be the configuration space of Definition 2.1. Let  $e = e(i)$  be the edge of  $\Gamma$  numbered by  $i$ . It goes from the vertex  $v(j)$  numbered by  $j$  to  $v(k)$ . Consider the map

$$p(\Gamma, i) = p(\Gamma, e(i)): C_{2n}(M, \Gamma) \rightarrow C_2(M)$$

that lifts  $(m_1, \dots, m_{3n}) \mapsto (m_j, m_k)$ , continuously. Let  $H_i(\Gamma) \subset C_{2n}(M, \Gamma)$  be the preimage of  $H_i$  under  $p(\Gamma, i)$ . This is a chain (here, a combination of manifolds with boundaries) whose points (that project to)  $(m_1, \dots, m_{3n})$  are continuously equipped with rational homology classes of paths from  $m_j$  to  $m_k$ . It is cooriented in  $C_{2n}(M, \Gamma)$  (that is oriented like  $M^{2n}$ ) by the coorientation of  $H_i$  in  $C_2(M)$ .

Then the intersection of the  $H_i(\Gamma)$ , for  $i \in \{1, 2, \dots, 3n\}$ , is a compact subspace  $I(\Gamma, \{H_j\})$  of  $C_{2n}(M, \Gamma)$ . Its image  $p(\Gamma, i)(I(\Gamma, \{H_j\}))$  in  $H_i$  is a compact subset of  $H_i$ .

**Definition 2.2.** The  $H_i$  are said to be in *general 3n-position* if, for any  $\Gamma \in \mathcal{S}_n$ ,

- $I(\Gamma, \{H_j\})$  is finite,
- $p(\Gamma, i)(I(\Gamma, \{H_j\}))$  is made of points in the interiors of the simplices of  $H_i$ , for any  $i \in \{1, 2, \dots, 3n\}$  and,
- all the  $H_i(\Gamma)$  intersect transversally at the corresponding points that are in the interior of  $C_{2n}(M, \Gamma)$ .

The fact that such  $H_i$  exist will be proved in Subsection 2.5.

Fix  $\Gamma \in \mathcal{S}_n$ . Under the given assumptions, the cooriented  $H_i(\Gamma)$  only intersect transversally at distinct points in the interior of  $C_{2n}(M, \Gamma)$ . We define their equivariant algebraic intersection  $I_\Gamma(\{H_i\}) \in \mathcal{A}_n^h$  as follows.

Consider an intersection point  $m$ , it is equipped with a sign  $\varepsilon(m)$  as usual, and it is also equipped with the following additional data: Our intersection point  $m$  projects to some  $(m_1, \dots, m_{2n}) \in M^{2n}$ . Associate  $m_j$  with  $v(j)$ . Since  $m$  belongs to  $H_i(\Gamma)$ , the edge  $e(i)$  is equipped with a rational homology class of paths from  $m_j$  to  $m_k$ . Each edge of  $\Gamma$  is equipped with a rational homology class of paths between its ends in this way. Choose a simply connected graph  $\gamma$  (e. g. a spider) in  $M$  that contains a basepoint and all the points  $m_j$  of  $M$ . A path from  $m_j$  to  $m_k$  can be composed with paths in the graph  $\gamma$  to become a loop based at the basepoint whose rational homology class is well-determined by the rational homology class of the path and by  $\gamma$ . It reads  $n(m, e(i), \gamma)[K]$  for some integer  $n(m, e(i), \gamma)$ . Let  $\Gamma(m, \gamma)$  be the graph obtained from  $\Gamma$  by putting  $\frac{t^{-n(m, e(i), \gamma)}}{k(t-1)\delta(t)}$  on the left-hand side of the oriented edge  $e(i)$  for each edge. Orient the vertices of  $\Gamma$  so that the permutation of the half edges from (first half of first edge, second half of first edge,  $\dots$ , second half of last edge) to

(half-edges of the first vertex ordered in a way compatible with the vertex orientation, ...) is even.

Note that the class of  $\Gamma(m, \gamma)$  in  $\mathcal{A}_n^h$  does not depend on  $\gamma$ . Indeed, changing the path that goes from  $m_j$  to the basepoint in  $\gamma$  amounts to add some fix integer to  $n(m, e, \gamma)$  for the edges  $e$  going to  $m_j$  and to remove this integer from  $n(m, e, \gamma)$  for the edges starting at  $m_j$ . Because of Relations 1 and 3, it does not change the class of  $\Gamma(m, \gamma)$  that will be denoted by  $[\Gamma(m)]$ . Finally, assign  $\varepsilon(m)[\Gamma(m)] \in \mathcal{A}_n^h$  to  $m$ .

Then define  $I_\Gamma(\{H_i\}) \in \mathcal{A}_n^h$  as the sum over the intersection points of the  $\varepsilon(m)[\Gamma(m)]$ .

**Theorem 2.3.** *Then*

$$\tilde{z}_n(M, \mathbb{K}, \tau) = \sum_{\Gamma \in \mathcal{S}_n} \frac{I_\Gamma(\{H_i\})}{2^{3n}(3n)!(2n)!} \in \mathcal{A}_n^h$$

is an invariant of  $(M, \mathbb{K}, \tau)$ . Let  $\xi_n$  be the element of  $\mathcal{A}_n^h$  defined in [L1, Section 1.6]. It is an element of the subspace of  $\mathcal{A}_n^h$  generated by the diagrams whose edges are beaded by 1. Then

$$\tilde{z}_n(M, \mathbb{K}) = \tilde{z}_n(M, \mathbb{K}, \tau) + \frac{p_1(\tau)}{4} \xi_n$$

is an invariant of  $(M, \mathbb{K})$ .

Set  $\tilde{z}_0(M, \mathbb{K}) = 0$ . Exponentiating  $(\tilde{z}_n(M, \mathbb{K}))_{n \in \mathbb{N}}$  should give an invariant equivalent to the Garoufalidis and Kricker rational lift of the Kontsevich integral.

Note that with the injection  $\psi$  of the end of Subsection 2.1 we have

$$\mathcal{Q}(M, \mathbb{K}) = \psi(\tilde{z}_1(M, \mathbb{K})).$$

The properties of the chains  $H_i$  that are proved in [L3] will allow us to generalize properties of  $\mathcal{Q}(M, \mathbb{K})$  to  $(\tilde{z}_n(M, \mathbb{K}))_{n \in \mathbb{N}}$  in a future work.

**2.4. Regular points of  $(S^2)^{3n}$ .** Let  $S_j(\mathbb{R}^3)$  be the compactification of the quotient of  $((\mathbb{R}^3)^j \setminus \text{all diagonals})$  by the homotheties with positive ratio and the global translations, obtained by successive blow-ups of all the diagonals as in Subsection 2.2. (When  $\mathbb{R}^3$  is identified to the tangent space of a point  $m$ ,  $S_j(\mathbb{R}^3)$  is the preimage of  $(m)_{i=1, \dots, j}$  in  $C_j(M)$ .) It is a compact smooth manifold with corners of dimension  $(3j - 4)$ . Every graph  $G$  with  $j$  vertices, numbered from 1 to  $j$ , and with  $i$  oriented edges (with distinct ends), numbered in a set  $A$ , determines a map “direction of the edges”

$$p(G): (\mathbb{R}^3)^j \setminus \text{all diagonals} \rightarrow (S^2)^A$$

that factors through the homotheties with positive ratio and global translations and whose factorisation smoothly extends to define a smooth map

$$p(G): S_j(\mathbb{R}^3) \rightarrow (S^2)^A$$

still denoted by  $p(G)$ .

Thus, when  $j \leq 2n$  and when  $A \subset \{1, \dots, 3n\}$ , every such graph  $G$  determines the map  $g_G$

$$g_G = p(G) \times \text{Identity}((S^2)^B): S_j(\mathbb{R}^3) \times (S^2)^B \rightarrow (S^2)^A \times (S^2)^B$$

where  $B = \{1, \dots, 3n\} \setminus A$ . A *regular value* of this map  $g_G$  is a point  $Y$  of the target  $(S^2)^{3n}$  such that for any point  $y$  of  $g_G^{-1}(Y)$ , the tangent map of  $g_G$  at  $y$  is surjective. Note that when the dimension of the source is smaller than the dimension of the target, the set of regular values is the complement of the image.

**Lemma 2.4.** *The set of regular values of  $g_G$  is open and dense in  $(S^2)^{3n}$ .*

PROOF. The density is a direct corollary of the Morse-Sard theorem [Hi, Chapter 3, Section 1]. Let us check openness. The set where the tangent map is not surjective is closed in the compact source and therefore compact, so that its image is compact, and the set of regular values is open.  $\square$

Thus the finite intersection of the sets of regular values of such maps  $g_G$  is also dense and open.

**Definition 2.5.** An element of  $(S^2)^{3n}$  is *regular* if it is a regular value for all these maps  $g_G$ .

**Lemma 2.6.** *If  $(X_1, \dots, X_{3n})$  is regular, then the  $H_i(\Gamma)$  do not intersect over the small diagonal of  $M^{2n}$  in  $C_{2n}(M)$ .*

PROOF. If they did, there would be an intersection point in the small diagonal of  $C_{2n}(M)$ . Such a point would be a configuration in the tangent space  $T_m M$  of  $M$  at some point  $m$  of  $M$ , where  $T_m M$  is identified to  $\mathbb{R}^3$  via  $\tau$ . Since  $(X_1, \dots, X_{3n})$  is regular, it belongs neither to the  $(6n - 4)$ -dimensional image of  $p(\Gamma)$ , nor to the  $(6n - 2)$ -dimensional image of  $g_{\Gamma \setminus e(i)}$  for some edge  $e(i)$  when  $m$  belongs to  $K_i$ .  $\square$

**2.5. Transversality.** In this subsection, we prove that there exist  $H_i$  in general  $3n$ -position.

It follows from general transversality properties that the  $H_i(\Gamma)$  can be perturbed so that they have a finite number of transverse intersection points (see [Hi, Chapter 3]). The subtleties here are

- that we want simultaneous transversality for all the  $\Gamma \in \mathcal{S}_n$ ,
- that we would like to perturb the  $H_i$  rather than the  $H_i(\Gamma)$ <sup>1</sup>.

To prove the existence of  $H_i$  in general  $3n$ -position, we proceed as follows.

Choose cycles  $H_i^0$ , together with their simplicial decompositions, with the given boundaries, so that the  $H_i^0$  are transverse to  $\partial\tilde{C}_2(M)$ . (In particular, they read as products  $[0, 1] \times \partial H_i^0$  near  $\partial\tilde{C}_2(M)$ .)

Assume that

- the 4-dimensional simplices of  $H_i^0$  are  $C^\infty$  embeddings indexed by elements  $j$  of some finite set  $S(i)$

$$\Delta_j^0(i): \Delta^4 \rightarrow O_j(i) \subset C_2(M)$$

---

<sup>1</sup>The  $H_i(\Gamma)$  are associated with  $H_i$  and  $\Gamma$ , and the face identifications, that will be performed later, could not be performed without the fact that  $H_i(\Gamma)$  is precisely the preimage of some fixed  $H_i$



of the standard 4-simplex  $\Delta^4$  in open regions  $O_j(i)$  of  $C_2(M)$  such that there are  $C^\infty$  embeddings

$$\Phi_j(i): O_j(i) \rightarrow \mathbb{R}^6$$

with open image in some intersection of half-spaces in  $\mathbb{R}^6$ ,

- there is a set  $B$  of 3-dimensional faces of the 4-dimensional simplices that constitute a simplicial decomposition of  $\partial H_i$ ,
- there is a bijection  $b_i$  of the set of the 3-dimensional faces of the  $\Delta_j^0(i)$  that are not in  $B$  to  $A \times \{+, -\}$ , for some finite set  $A$ , such that for any  $a \in A$ , the face labeled by  $(a, +)$  has the same image in  $C_2(M)$  than the face labeled by  $(a, -)$  with opposite boundary orientation and matching local coefficients (this is the *face identification*),
- the simplices  $\delta_r(i)$  of dimension  $k$  ( $k \leq 4$ ) of  $H_i$  are codimension 0 submanifolds with boundaries of the preimage of a regular point  $N_{i,r}$  under a constraint map  $f(\delta_r(i))$  from the intersection of the open sets  $O_j(i)$  such that  $\delta_r(i)$  is a face of  $\Delta_j(i)$  to  $S^{6-k}$ .

Define  $\mathcal{M}(H_i^0)$  as the set of deformations  $H_i = \{\Delta_j(i): \Delta^4 \rightarrow O_j(i)\}_{j \in S(i)}$  of the  $H_i^0 = \{\Delta_j^0(i)\}_{j \in S(i)}$ , where the set  $S(i)$  of simplices, the face identification and the simplices of  $\partial H_i$  are fixed.

Equip  $\mathcal{M}(H_i^0)$  with the  $C^\infty$  topology that is its topology of a subset of  $\prod_{j \in S(i)} C^\infty(\Delta^4, O_j(i))$  where the topology of  $C^\infty(\Delta^4, O_j(i))$  is defined in [Hi, Chapter 2, Section 1].

Consider the topological space

$$\mathcal{M} = \prod_{i=1}^{3n} \mathcal{M}(H_i^0).$$

Define the subset  $\mathcal{M}_*$  of  $\mathcal{M}$  made of the  $(H_1, H_2, \dots, H_{3n})$  whose simplices satisfy: For each  $\Gamma \in \mathcal{S}_n$ , for any  $3n$ -tuple  $(\delta_{j_i}(i) \subset H_i)_{i \in \{1, \dots, 3n\}}$  of simplices,  $*(\Gamma, \delta_{j_i}(i))$ : the  $p(\Gamma, i)^{-1}(\delta_{j_i}(i))$  are transverse in  $C_{2n}(M, \Gamma)$ .

**Proposition 2.7.**  $\mathcal{M}_*$  is open and dense in  $\mathcal{M}$ . In particular, there exists a  $(3n)$ -tuple  $(H_1, H_2, \dots, H_{3n})$  in general  $3n$ -position.

PROOF. It is enough to prove that the subspace of  $\mathcal{M}$  made of the  $(H_1, H_2, \dots, H_{3n})$  that satisfy  $*(\Gamma, \delta_{j_i}(i))$  is open and dense for each  $\Gamma \in \mathcal{S}_n$ , for any  $3n$ -tuple  $(\delta_{j_i}(i) \subset H_i)_{i \in \{1, \dots, 3n\}}$  of simplices.

It is obviously open and we only need to prove that it is dense.

Consider the regions where the  $\delta_{j_i}(i)_{i \in \{1, \dots, 3n\}}$  live. The intersection of their preimages under the  $p(\Gamma, i)$  determines an open subspace of  $C_{2n}(M, \Gamma)$  where the transversality of the  $\delta_{j_i}(i)$  reads:  $(N_{i, j_i})_{i \in \{1, \dots, 3n\}}$  is a regular value of the constraint map  $\prod_{i=1}^{3n} f(\delta_{j_i}(i)) \circ p(\Gamma, i)$ . According to the Morse-Sard theorem, the set of regular  $(N_i)_{i \in \{1, \dots, 3n\}}$  is dense. It is furthermore open.

Therefore, if none of the  $\delta_{j_i}(i)$  touches the boundary, it is easy to slightly move the simplices by changing the preimage of  $N_{i, j_i}$  to the preimage of some closed point. (This can

be done by a global isotopy of  $C_2(M)$  supported near  $\delta_{j_i}(i)$  that moves  $\delta_{j_i}(i)$  to the preimage of some close point.)

In general, we have a set of simplices in the boundary, with indices in  $I_b$ , a set of simplices that don't touch the boundary with indices in  $I_e$ , and the other ones with indices in  $I_t$  that have a maximal face  $\mathcal{F}_i$  in the boundary. Since  $(X_1, \dots, X_{3n})$  is regular, the intersection of the  $p(\Gamma, i)^{-1}(\partial H_i)$ , for  $i \in I_b \cup I_t$  is transverse in the faces of the boundary of  $C_{2n}(M, \Gamma)$ . Therefore, it is a  $(6n - 2(\#I_b + \#I_t) - c)$ -submanifold of the codimension  $c$  faces of  $\partial C_{2n}(M, \Gamma)$ . The intersection of the  $\delta_{j_i}(i)$ , for  $i \in I_e$  will be transverse to this manifold if the restriction of  $\prod_{i \in I_e} f(\delta_{j_i}(i)) \circ p(\Gamma, i)$  to this manifold is regular, and this can be achieved as before<sup>2</sup>. Therefore the transversality holds in a neighborhood of the  $\mathcal{F}_i$ , and we can make it hold for all the simplices by applying the above argument to  $(I_b, I_e \cup I_t)$  instead of  $(I_b \cup I_t, I_e)$ , the openness allowing us to recorrect the  $\delta_{j_i}(i)$  for  $i \in I_t$  near the boundaries without losing transversality.  $\square$

**2.6. Proof of invariance.** In this section, we prove that we have defined a topological invariant of  $(M, \mathbb{K}, \tau)$ . The only thing that we need to show is that our definition is independent of  $(X_1, \dots, X_{3n})$  and  $(H_1, \dots, H_{3n})$ , i.e. that it is independent of  $(H_1, \dots, H_{3n})$  when  $(X_1, \dots, X_{3n})$  is not fixed.

Since the invariance is obvious when  $(H_1, \dots, H_{3n})$  moves in a neighborhood of  $(H_1, \dots, H_{3n})$  in general  $3n$ -position, it is enough to prove invariance when  $H_1$  is changed to some  $H'_1$  such that  $(H'_1, H_2, \dots, H_{3n})$  is in general  $3n$ -position.

First pick a  $C^\infty$ -path  $P(X_1, X'_1)$  from  $X_1$  to  $X'_1$  in  $(S^2 \setminus \{W, -W\})$  whose image is some codimension 0 submanifold with boundary of a submanifold defined by  $f(x) = 0$  for some smooth map  $f$  that is defined in a regular neighborhood of the image of this path and valued in  $[-1, 1]$ . Without loss assume that  $(0, X_2, X_3, \dots, X_{3n})$  is a regular value for all the compositions of the maps  $g_G$  by  $f$  on the first coordinate. (If it is not the case, use the Morse-Sard theorem to find a close regular value and move everything slightly.)

**Lemma 2.8.** *There exists a 5-cochain  $C$  in general  $3n$ -position with  $H_2, \dots, H_{3n}$  such that*

$$\partial C = H'_1 - H_1 \cup \pm k(t-1)\delta(t)s_\tau(M; P(X_1, X'_1)).$$

PROOF. The wanted boundary  $\partial C$  is a 4-cycle of  $\tilde{C}_2(M)$  with a zero equivariant intersection with  $A(K)$ . Therefore it does not meet  $\cup_{k \in \mathbb{Z}} \theta^k(A(K))$ , algebraically, and it can be moved away from  $\partial \tilde{C}_2(M)$  so that its image does not meet the preimage of  $K^2$  in  $\widetilde{M^2}$ , algebraically, and vanishes in  $H_4(\widetilde{M^2}; \mathbb{Q}) = \mathbb{Q}[S \times S]$ , where  $S$  is a closed surface dual to  $K$ . See [L3, Proposition 2.6]. Then  $\partial C$  bounds a rational 5-chain in  $\widetilde{M^2}$ . This chain can be assumed to meet the preimage of the diagonal along  $P(\theta)S$  for some polynomial  $P$  with rational coefficients. Then  $\partial C$  is homologous to  $P(\theta)(ST(M))_{|S}$ , and  $P = 0$  since  $\partial C$  vanishes in  $H_4(C_2(M); \mathbb{Q}(t))$ .  $\square$

<sup>2</sup>Here, since the sum of codimensions of the  $\delta_{j_i}(i)$ , for  $i \in I_e$  is greater or equal than  $(2\#I_e)$  that is greater than  $6n - 2(\#I_b + \#I_t) - 1$ , this means that the  $p(\Gamma, i)^{-1}(\delta_{j_i}(i))$  for  $i \in I_e$  can be assumed not to meet the intersection  $\cap_{i \in I_b \cup I_t} p(\Gamma, i)^{-1}(\partial H_i)$ .

Here the notion of general  $3n$ -position is similar to the previous notion and can be achieved in the same way.

In particular, the intersection of  $p(\Gamma, 1)^{-1}(C)$  and the  $H_i(\Gamma)$  for  $i \geq 2$  is some  $C^\infty$  compact 1-manifold with boundary in  $C_{2n}(M, \Gamma)$ .  $p(\Gamma, 1)^{-1}(C)$  is locally seen as the zero locus of some real function except near  $p(\Gamma, 1)^{-1}(\partial C)$  where some additional independent real function must be positive. Therefore,

$$\begin{aligned} & \partial(p(\Gamma, 1)^{-1}(C) \cap \bigcap_{i=2}^{3n} H_i(\Gamma)) = \\ & H'_1(\Gamma) \cap \bigcap_{i=2}^{3n} H_i(\Gamma) - H_1(\Gamma) \cap \bigcap_{i=2}^{3n} H_i(\Gamma) + p(\Gamma, 1)^{-1}(C) \cap \partial C_{2n}(M, \Gamma) \cap \bigcap_{i=2}^{3n} H_i(\Gamma). \end{aligned}$$

Let us check that the first sign is correct. The two other ones are similar. The normal bundle of the one-manifold reads  $N_C^1 \oplus \bigoplus_{i=2}^{3n} N^i$  where  $N_C^1$  is the normal bundle to  $p(\Gamma, 1)^{-1}(C)$  in  $C_{2n}(M, \Gamma)$ . Since  $H'_1$  is oriented as the boundary of  $C$ ,  $C$  is oriented as the outward normal  $N_o$  to  $C$ , followed by the orientation of  $H'_1$  along  $H'_1$ . Therefore the normal bundle of  $p(\Gamma, 1)^{-1}(H'_1)$  is oriented by  $N_C^1 \oplus N_o$ . Use the notation  $\langle \frac{1}{\delta} H_1(\Gamma), \dots, \frac{1}{\delta} H_{3n}(\Gamma) \rangle_{\mathcal{A}, C_{2n}(M, \Gamma)}$ , where  $\hat{\delta} = k(t-1)\delta(t)$  and the subscript  $C_{2n}(M, \Gamma)$  will be sometimes forgotten, to denote  $I_\Gamma(\{H_i\})$ , that was defined before the statement of Theorem 2.3. Then with similar notation

$$I_\Gamma(\{H'_i\}) - I_\Gamma(\{H_i\}) = -\langle \frac{1}{\delta} p(\Gamma, 1)^{-1}(C) \cap \partial C_{2n}(M, \Gamma), \frac{1}{\delta} H_2, \dots, \frac{1}{\delta} H_{3n} \rangle_{\mathcal{A}}$$

where the intersection points in

$$p(\Gamma, 1)^{-1}(C) \cap \partial C_{2n}(M; \Gamma) \cap H_2(\Gamma) \cap \dots \cap H_{3n}(\Gamma)$$

only occur inside codimension 1 faces of  $\partial C_{2n}(M, \Gamma)$ .

Let us study some point  $P$  in this intersection. Its codimension one face corresponds to some connected subgraph  $\Gamma_I$  made of the vertices numbered in a set  $I$  and the edges between two of these, as in Subsection 2.2. Define the graph  $\Gamma(I) = \Gamma/\Gamma_I$  obtained from  $\Gamma$  by identifying  $\Gamma_I$  to a point  $v(I)$ . The vertices of  $\Gamma(I)$  are the vertices of  $\Gamma$  numbered in  $\{1, \dots, 2n\} \setminus I$  and the additional vertex  $v(I)$ , and the edges of  $\Gamma(I)$  are the edges of  $\Gamma$  that are not edges of  $\Gamma_I$ . The set  $E(\Gamma)$  of edges of  $\Gamma$  is the disjoint union of the sets  $E(\Gamma_I)$  and  $E(\Gamma(I))$ .

Our face  $\mathcal{F}(\Gamma, I)$  fibers over the space of configurations of the vertices of  $\Gamma(I)$  that form the set  $V(\Gamma(I))$ , and our intersection point projects to  $M^{V(\Gamma(I))}$ . The fiber is made of the infinitesimal configurations of  $I$  up to translation and dilation. The dimension of the fiber is  $(3\sharp I - 4)$  and the dimension of the base is  $3(\sharp V(\Gamma(I))) = 6n - 3\sharp I + 3$ .

Since the intersection is transverse, the edges give  $(6n - 1)$  independent constraints on our intersection point  $P$ , where the edge numbered by 1 gives one of these constraints and each of the other ones gives two constraints.

The constraints coming from the edges of  $\Gamma(I)$  only concern the base, while the constraints of  $E(\Gamma_I)$  only concern the fiber except possibly for one edge ( $e(j) \in E(\Gamma_I)$ ) where the constraint can read: “The point  $v(I) \in K_j$ .”

In this case, this constraint is a constraint for the base, and  $j \neq 1$ . If we have such an exceptional constraint “ $v(I) \in K_j$ ”, set  $\chi_k = 1$ . Otherwise, set  $\chi_k = 0$ .

If the edge  $e(1)$  belongs to  $E(\Gamma_I)$ , set  $\chi_A = 1$ , and if it belongs to  $E(\Gamma(I))$ , set  $\chi_A = 0$ .

Then we have  $2\sharp E(\Gamma_I) - 2\chi_k - \chi_A$  constraints on the  $(3\sharp I - 4)$ -dimensional fiber.

The transversality condition tells us that  $2\sharp E(\Gamma_I) - 2\chi_k - \chi_A = 3\sharp I - 4$  that is

$$4 - 2\chi_k - \chi_A = 3\sharp I - 2\sharp E(\Gamma_I)$$

where the right-hand side is the valency of the vertex  $v(I)$  in  $\Gamma(I)$  as a count of half-edges shows. This valency must be 4, 3, 2 or 1.

The transversality also tells us that the map “direction of the edges” from the  $(3\sharp I - 4)$ -manifold  $S_I(\mathbb{R}^3)$  to the product of the images of the constraint functions must be a local diffeomorphism.

In particular, unless  $\sharp I = 2$ , there can be no vertex of valency 1 in  $\Gamma_I$  because moving this vertex in the direction of the unique edge incident to such a vertex would not change the image of the above map.

Thus, either  $\Gamma_I$  is an edge, and this case will be treated by the IHX (or Jacobi) identification, or  $\Gamma_I$  is connected, all the vertices of  $\Gamma_I$  have valency 2 or 3 and there are  $\chi$  vertices of valency 2 where  $1 \leq \chi \leq 4$ , and this case will be treated by the parallelogram identification.

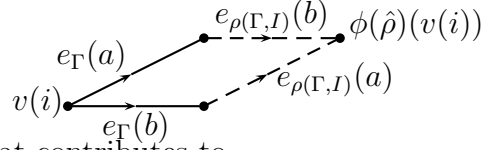
Let us explain how these classical identifications allow us to prove that the sum of the contributions of all such intersection points  $P$  to  $\sum_{\Gamma \in \mathcal{S}_n} (I_\Gamma(\{H'_i\}) - I_\Gamma(\{H_i\}))$  vanishes in our setting. We start with the parallelogram case.

**Lemma 2.9.** *Let  $E$  be the set of codimension one faces  $\mathcal{F}(\Gamma, I)$  of spaces  $C_{2n}(M, \Gamma)$  indexed by some  $(\Gamma, I)$  where  $\Gamma \in \mathcal{S}_n$ ,  $I$  is a subset of  $\{1, 2, \dots, 2n\}$ ,  $\Gamma_I$  is connected, the vertices of  $\Gamma_I$  have valency 2 or 3 and at least one vertex of  $\Gamma_I$  has valency 2. There is an involution  $\hat{\rho}$  of  $E$  without fixed point such that the possible intersection points in two faces  $\mathcal{F}_1$  and  $\hat{\rho}(\mathcal{F}_1)$  leave the sum  $\tilde{z}_n(M, \mathbb{K}, \tau)$  invariant.*

PROOF. Fix  $\Gamma$  and  $I$  as above. Let  $i$  be the smallest element of  $I$  such that the valency of  $v(i)$  in  $\Gamma_I$  is 2. Define the labelled graph  $\rho(\Gamma, I) \in \mathcal{S}_n$  from  $\Gamma$  by modifying the two edges  $e(a)$  and  $e(b)$  incident to  $v(i)$  in  $\Gamma_I$  as follows: if  $e(a)$  reads  $\varepsilon(a)\overrightarrow{v(i)v(j)}$  and if  $e(b)$  reads  $\varepsilon(b)\overrightarrow{v(i)v(k)}$  in  $\Gamma$ , then  $e(a)$  reads  $\varepsilon(a)\overrightarrow{v(k)v(i)}$  and  $e(b)$  reads  $\varepsilon(b)\overrightarrow{v(j)v(i)}$  in  $\rho(\Gamma, I)$ . Define  $\hat{\rho}$  so that

$$\hat{\rho}(\mathcal{F}(\Gamma, I)) = \mathcal{F}(\rho(\Gamma, I), I).$$

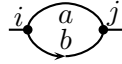
Consider the orientation-reversing involutive diffeomorphism  $\phi(\hat{\rho})$  from  $\mathcal{F}(\Gamma, I)$  to  $\hat{\rho}(\mathcal{F}(\Gamma, I))$  that maps a point  $P$  to the point where the only changed piece of data is the position of  $v(i)$  in the infinitesimal configuration of  $I$  where  $v(i)$  is mapped to its symmetric with respect to the middle of the two (possibly coinciding) other ends of  $e(a)$  and  $e(b)$ . The standard properties of a parallelogram guarantee that for any edge label  $j$ ,  $p(\Gamma, j) = p(\rho(\Gamma, I), j) \circ \phi(\hat{\rho})$  on  $\mathcal{F}(\Gamma, I)$ .



Consider a point  $P$  of  $\mathcal{F}(\Gamma, I)$  that contributes to

$$\left\langle -\frac{1}{\delta} p(\Gamma, 1)^{-1}(C) \cap \partial C_{2n}(M, \Gamma), \frac{1}{\delta} H_2, \dots, \frac{1}{\delta} H_{3n} \right\rangle_{\mathcal{A}}.$$

Recall that the chains  $C$  and  $H_i$  are transverse to  $\partial C_2(M)$ . They are made of two kinds of pieces there:  $I_\Delta ST(K_i)$  and  $s_\tau(M; P(X_1, X'_1))$  or  $s_\tau(M; X_i)$ . Since our assumptions imply that the intersection is transverse, if  $\sharp I > 2$ ,  $P$  cannot be in the parts  $p(\Gamma, a)^{-1}(ST(M)|_{K_a})$  or  $p(\Gamma, b)^{-1}(ST(M)|_{K_b})$  because in this case the constraint coming from the other edge adjacent to  $P$  gives the direction of this other edge and stretching this other edge leads to a non trivial kernel of the constraint map. Therefore, if  $\sharp I > 2$ , the two edges can be assumed to be weighted by  $1 = \frac{k(t-1)\delta(t)}{k(t-1)\delta(t)}$ . Thus, when a point  $P$  as above contributes to the variation of  $I_\Gamma(\{H\})$ , the point  $\phi(\hat{\rho})(P)$  contributes with the same beaded graph with the opposite sign to the variation of  $I_{\rho(\Gamma, I)}(\{H\})$ . (Indeed, the product of the constraint maps only differ by the orientation-reversing diffeomorphism  $\phi(\hat{\rho})$  of the faces, and the graphs are obtained from one another by a possible exchange of two edges and a possible simultaneous reverse of two edge orientations, for two edges beaded by 1.) If  $\sharp I = 2$ , our assumptions imply that  $\Gamma_I$  is made of two edges  $e(a)$  and  $e(b)$  between the two elements  $i$  and  $j$  of  $I$  like in the figure.



In  $\rho(\Gamma, I)$ , the orientations of both edges are reversed. Up to exchanging  $a$  and  $b$ ,  $P \in p(\Gamma, a)^{-1}(s_\tau(M; X_a)) \cap I_\Delta p(\Gamma, b)^{-1}(ST(M)|_{K_b})$ , and the rational functions are  $\pm 1$  and  $\pm I_\Delta$ .

Let us show that we have the same cancellation as before in this case. Let  $K_b \times D_b$  denote a trivialised tubular neighborhood of  $K_b$ . Then the local constraint map associated to  $(-1/(I_\Delta \hat{\delta}))H_b$  near  $ST(M)|_{K_b}$  can be viewed as a map  $f'_b: ST(M) \rightarrow D_b$  associated with the natural projection of  $K_b \times D_b$  onto the disk  $D_b$ .

Let  $P'$  be a transverse intersection point in  $p(\Gamma, a)^{-1}(s_\tau(M; X_a)) \cap p(\Gamma, b)^{-1}(ST(M)|_{K_b})$ . Let  $\varepsilon$  be the local degree of  $(\prod_{e \neq b} f_e \circ p(\Gamma, e), f'_b \circ p(\Gamma, b))|_{\mathcal{F}(\Gamma, I)}$  at  $P'$ , where the  $f_e$  are local constraint maps associated to the  $H_e$ . Then  $P'$  contributes as



As before, the local degree of  $(\prod_{e \neq b} f_e \circ p(\rho(\Gamma, I), e), f'_b \circ p(\rho(\Gamma, I), b))|_{\mathcal{F}(\rho(\Gamma, I), I)}$  at  $\phi(\hat{\rho})(P')$  is  $(-\varepsilon)$  since this map is the composition of the former one by  $\phi(\hat{\rho})$ .

Let  $\iota$  denote the orientation-reversing involution of  $C_2(M)$  that extends the exchange of points in  $M^2 \setminus \text{diag}$  and let  $\iota_{S^2}$  denote the antipode of  $S^2$ .

Focus on the edges  $e(a)$  and  $e(b)$ . Without loss, consider  $\varepsilon$  as the degree of

$$f_a \times f'_b: (ST(D_b) =_\tau S^2 \times D_b) \rightarrow S^2 \times D_b$$

where  $(ST(M) = \partial C_2(M))$  and  $ST(D_b)$  are oriented by the orientation of  $e_\Gamma(b)$ , and  $f_a$  is the projection of  $ST(D_b)$  on  $S^2$  if the orientations of  $e_\Gamma(a)$  and  $e_\Gamma(b)$  coincide, and its composition by  $\iota_{S^2}$  otherwise.

With these orientations and conventions,  $e_{\rho(\Gamma, I)}(b)$  is equipped with

$$-I_\Delta(t)\iota(ST(M)|_{K_b}) = -I_\Delta(t^{-1})ST(M)|_{K_b}$$

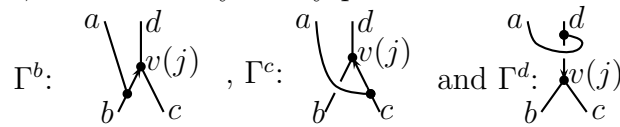
while  $(-\varepsilon)$  is the degree of

$$(f_a \circ \iota) \times (f'_b \circ \iota) = (\iota_{S^2} \circ f_a) \times f'_b.$$

Then  $\phi(\hat{\rho})(P')$  contributes as  $(-\varepsilon) \begin{array}{c} \circlearrowleft \\ \text{---} \end{array} = (-\varepsilon) \begin{array}{c} \text{---} \\ \circlearrowright \\ -I_\Delta(t) \end{array} . \quad \square$

**Lemma 2.10.** *The intersection points of the faces  $\mathcal{F}(\Gamma, I)$  where  $\Gamma_I$  is an edge do not make the sum  $\tilde{z}_n(M, \mathbb{K}, \tau)$  vary, thanks to the IHX relation.*

PROOF. Let  $f$  be the label of the unique edge of  $\Gamma_I$ . Like in the previous proof, notice that an intersection point  $P$  in such a face cannot come from the  $p(\Gamma, f)^{-1}(ST(M)|_{K_f})$  part. In particular, the edge  $e(f) = \Gamma_I$  is beaded by 1. Consider the graph  $\Gamma(I) = \Gamma/\Gamma_I$ . Its vertex  $v(I)$  has 4 incident edges  $e(a)$ ,  $e(b)$ ,  $e(c)$ ,  $e(d)$ , and, with the natural identifications, in the initial graph  $\Gamma$ ,  $e(f)$  goes from  $v(i)$  to  $v(j)$  where  $v(i)$  is incident to two edges among  $e(a)$ ,  $e(b)$ ,  $e(c)$ ,  $e(d)$  and  $v(j)$  is incident to the two other ones. For  $g = b, c$  or  $d$ , let  $\Gamma^g$  be the graph of  $\mathcal{S}_n$  such that  $\Gamma^g(I = \{i, j\}) = \Gamma(I)$ , and  $v(i)$  is incident to  $e(a)$  and  $e(g)$ . It is enough to prove that the contributions of the possible intersection points of the three faces indexed by  $(\Gamma^g, I)$  cancel in the sum  $\tilde{z}_n(M, \mathbb{K}, \tau)$ . Our intersection point  $P$  of  $C_{2n}(M, \Gamma)$  will give a transverse intersection point in the three faces, with a common sign, and  $\Gamma^b$ ,  $\Gamma^c$  and  $\Gamma^d$  are oriented so that their vertex orientations coincide outside the disk of the following picture, and they are given by the picture for the two vertices there. Indeed the roles of the half-edges indexed by  $b, c$  and  $d$  are cyclically permuted.



□

**2.7. The dependence on the trivialisation.** We now compute the variation of  $\tilde{z}_n(M, \mathbb{K}, \tau)$  under a change of trivialisation. Let  $\tau'$  be a trivialisation that coincides with  $\tau$  on a tubular neighborhood  $N(K)$  of  $K$ . We want to compute the variation caused by the replacement of the  $H_i$  by cycles  $H'_i$  of  $(C_2(M), \partial C_2(M))$  where  $\partial H'_i = k(t-1)\delta(t)(s_{\tau'}(M; X_i) - I_\Delta(t)ST(M)|_{K_i})$ . There exists a cobordism  $c_i$  between  $s_\tau(M; X_i)$  and  $s_{\tau'}(M; X_i)$  in  $ST(M)$  that is supported outside  $ST(N(K))$  [L3, Lemma 5.10], and there is a 5-chain  $C_i$  of  $C_2(M)$  such that

$$\partial C_i = H'_i - H_i \cup k(t-1)\delta(t)c_i.$$

Then

$$\tilde{z}_n(M, \mathbb{K}, \tau') - \tilde{z}_n(M, \mathbb{K}, \tau) = \sum_{\Gamma \in \mathcal{S}_n} \sum_{i=1}^{3n} \mathcal{V}(\Gamma, i)$$

where

$$\mathcal{V}(\Gamma, i) = \left\langle \frac{1}{\delta} H'_1, \dots, \frac{1}{\delta} H'_{i-1}, -\frac{1}{\delta} p(\Gamma, i)^{-1}(C_i) \cap \partial C_{2n}(M, \Gamma), \frac{1}{\delta} H_{i+1}, \dots, \frac{1}{\delta} H_{3n} \right\rangle_{\mathcal{A}, C_{2n}(M, \Gamma)}$$

like in the previous subsection. Now the proof of the previous subsection can be applied verbatim to cancel most of the contributions, except for the computation of the valency of  $v(I)$  in  $\Gamma(I)$ , because if the tangent space of a point of  $M$  is identified to  $\mathbb{R}^3$  via  $\tau$ , the constraints coming from the chains  $H'_j$  or  $C_i$  constrain both the fiber and the base. Therefore, the valency of  $v(I)$  can be zero and this is the only case that is not covered by the cancellations of the previous subsection. In this case,  $\Gamma_I = \Gamma$ . Then  $\mathcal{V}(\Gamma, i)$  reads

$$\pm \langle s_{\tau'}(M; X_1), \dots, s_{\tau'}(M; X_{i-1}), p(\Gamma, i)^{-1}(c_i), s_{\tau}(M; X_{i+1}), \dots, s_{\tau}(M; X_{3n}) \rangle_{\mathcal{A}, \mathcal{F}(\Gamma, \{1, \dots, 2n\})}.$$

In particular, the variation, that does not involve any coefficient or non-trivial bead, is the same as the variation in the case of the universal finite type invariant of rational homology spheres, that was computed in [L1, Section 1.6]. This finishes the proof of Theorem 2.3.

### Appendix: A configuration space definition of the Casson-Walker invariant

For  $r \in \mathbb{R}$ , let  $B(r)$  denote the ball of radius  $r$  in  $\mathbb{R}^3$  that is equipped with its standard parallelisation  $\tau_s$ . A rational homology sphere  $N$  may be written as  $B_N \cup_{B(1) \setminus \text{Int}(B(1/2))} B^3$  where  $B_N$  is a *rational homology ball*, that is a connected compact (oriented) smooth 3-manifold with boundary  $S^2$  with the same rational homology as a point,  $B^3$  is a 3-ball,  $B_N$  contains  $(B(1) \setminus \text{Int}(B(1/2)))$  as a neighborhood of its boundary  $\partial B_N = \partial B(1)$ , and  $B^3$  contains  $(B(1) \setminus \text{Int}(B(1/2)))$  as a neighborhood of its boundary  $\partial B^3 = -\partial B(1/2)$ . Let  $B(N) = B_N(3)$  be obtained from  $B(3)$  by replacing the unit ball  $B(1)$  of  $\mathbb{R}^3$  by  $B_N$ . Equip  $B(N)$  with a trivialisaton  $\tau_N$  that coincides with  $\tau_s$  outside  $B_N$ .

Let  $W$  be a compact connected 4-manifold with signature 0 and with boundary

$$\partial W = B_N(3) \cup_{\{1\} \times \partial B(3)} (-[0, 1] \times \partial B(3)) \cup_{\{0\} \times \partial B(3)} (-B(3)).$$

Define  $p_1(\tau_N) \in (H^4(W, \partial W; \pi_3(SU(4))) = \mathbb{Z})$  as the obstruction to extend the trivialisaton of  $TW \otimes \mathbb{C}$  induced by  $\tau_s$  and  $\tau_N$  on  $\partial W$  to  $W$ . Again, we use the notation and conventions of [MS], see also [L1, Section 1.5].

Let  $C_2(B(N))$  be the compactification of  $(B(N)^2 \setminus \text{diagonal})$  obtained from  $B(N)^2$  by blowing-up the diagonal as in Definition 1.1. Consider a smooth map  $\chi: \mathbb{R} \rightarrow [0, 1]$  that maps  $] -\infty, -2]$  to 0 and  $[-1, \infty[$  to 1. Define

$$\begin{aligned} p_{B(3)}: \quad B(3)^2 \setminus \text{diagonal} &\rightarrow S^2 \\ (U, V) &\mapsto \frac{\chi(\|V\| - \|U\|)V - \chi(\|U\| - \|V\|)U}{\|\chi(\|V\| - \|U\|)V - \chi(\|U\| - \|V\|)U\|} \end{aligned}$$

This map extends to  $C_2(B(3))$  to a map still denoted by  $p_{B(3)}$ , that reads as the projection to  $S^2$  induced by  $\tau_s$  (see Subsection 1.5) on the unit tangent bundle of  $B(3)$ . A similar map

$p_N$  can be defined on the boundary  $\partial C_2(B(N))$ : The map  $p_N$  is the projection to  $S^2$  induced by  $\tau_N$  on the unit tangent bundle of  $B(N)$ , and the map  $p_N$  is given by the above formula, where we set  $\|U\| = 1$  when  $U \in B_N$ , for the other points of the boundary that are pairs  $(U, V)$  of  $(B(N))^2 \setminus \text{diagonal}$  where  $U$  or  $V$  belongs to  $\partial B(3)$  (therefore a possible point of  $B_N$  is replaced by  $0 \in \mathbb{R}^3$  in the formula).

The following theorem, that gives a configuration space definition for the Casson-Walker invariant, is due to Kuperberg and Thurston [KT] for the case of integral homology spheres (though it is stated in other words). It has been generalised to rational homology spheres in [L2, Section 6].

**Theorem 2.11.** *Let  $X, Y$  and  $Z$  be three distinct points of  $S^2$ . Under the above assumptions, for  $V = X, Y$  or  $Z$ , the submanifold  $p_N^{-1}(V)$  of  $\partial C_2(B(N))$  bounds a rational chain  $F_{N,V}$  in  $C_2(B(N))$ , and*

$$\lambda(N) = \frac{\langle F_{N,X}, F_{N,Y}, F_{N,Z} \rangle_{C_2(B(N))}}{6} - \frac{p_1(\tau_N)}{24}.$$

Note that it is easy to see that  $\langle F_{N,X}, F_{N,Y}, F_{N,Z} \rangle_{C_2(B(N))}$  is a well-defined invariant of  $(N, \tau_N)$ . Indeed,  $C_2(B(N))$  has the same rational homology as  $(\mathbb{R}^3)^2 \setminus \text{diagonal}$  that is homotopy equivalent to  $S^2$  via the map  $(x, y) \mapsto \frac{y-x}{\|y-x\|}$ . Therefore,  $C_2(B(N))$  has the same rational homology as  $S^2$ . In particular, since  $H_3(C_2(B(N)); \mathbb{Q}) = \{0\}$ , the cycle  $p_N^{-1}(V)$  bounds a rational chain in  $C_2(B(N))$  and, since  $H_4(C_2(B(N)); \mathbb{Q}) = \{0\}$ ,  $\langle F_{N,X}, F_{N,Y}, F_{N,Z} \rangle_{C_2(B(N))}$  only depends on the non-intersecting boundaries of the  $F_{N,V}$ .

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