

## 1. ORIENTATIONS

We begin by attempting to give complete rigour and detail to the definitions of orientation and the many connected theorems.

For this section, we will follow [1], [4] and [5].

**Definition 1.1** (Local Homology Group). For  $h_*(-)$  a homology theory and an  $n$ -manifold  $M$ , groups of the form  $h_k(M, M - \{x\})$  are called *local homology groups*.

For a chart  $\varphi: U \rightarrow \mathbb{R}^n$  on  $M$  centered at  $x$ , we get by excision that

$$h_k(M, M - \{x\}) \cong h_k(U, U - \{x\}) \xrightarrow{\varphi_*} h_k(\mathbb{R}^n, \mathbb{R}^n - \{0\}).$$

Hence for singular homology, we obtain  $H_n(M, M - \{x\}; G) \cong G$ .

**Definition 1.2** (Local  $R$ -orientation). Let  $R$  be a commutative ring. A generator of  $H_n(M, M - \{x\}; R) \cong R$  is called a *local  $R$ -orientation* of  $M$  about  $x$ .

Let  $K \subset L \subset M$ . The homomorphism  $r_K^L: h_k(M, M - L) \rightarrow h_k(M, M - K)$  induced by inclusion is called restriction. We write  $r_x^L$  when  $K = \{x\}$ .

**Proposition 1.3.** *When  $A$  is a compact, convex set contained in some chart  $\mathbb{R}^n \subset M$ , then  $r_x^A$  is an isomorphism for each  $x \in A$  and the groups are isomorphic to the coefficient group  $G$ .*

*Proof.*  $A$  is contained in the interior of some closed  $n$ -disk  $D \subset \mathbb{R}^n \subset M$ . Thus there is a commutative diagram

$$\begin{array}{ccc} h_n(M, M - A) & \longrightarrow & h_n(M, M - \{x\}) \\ \cong \uparrow & & \cong \uparrow \\ h_n(\mathbb{R}^n, \mathbb{R}^n - A) & \longrightarrow & h_n(\mathbb{R}^n, \mathbb{R}^n - \{x\}) \\ \cong \uparrow & & \cong \uparrow \\ h_n(D, \partial D) & \xlongequal{\quad} & h_n(D, \partial D) \end{array}$$

□

1.0.1. *The covering map perspective.*

**Definition 1.4** (Orientation bundle - the covering map perspective). We construct a covering  $\omega: h_k(M, M - \bullet) \rightarrow M$ . Define

$$h_k(M, M - \bullet) = \bigsqcup_{x \in M} h_k(M, M - \{x\})$$

where  $h_k(M, M - \{x\})$  is the fiber over  $x$  and is given the discrete topology.

Let  $U$  be an open neighborhood of  $x$  such that  $r_y^U$  is an isomorphism for each  $y \in U$ . Define bundle charts

$$\varphi_{x,U}: U \times G \rightarrow \omega^{-1}(U), \quad (y, a) \mapsto r_y^U (r_x^U)^{-1}(a).$$

We then give  $h_k(M, M - \bullet)$  the topology that makes  $\varphi_{x,U}$  in a homeomorphism onto an open subset. In particular, since  $h_k(M, M - x)$  is given the discrete topology, this is equivalent to the map  $\varphi_{x,U}(-, \alpha)$  being a homeomorphism onto an open

subset for each  $\alpha \in h_k(M, M - x)$ . It then remains to show that the transition maps

$$\varphi_{y,V}^{-1} \varphi_{x,U}: (U \cap V) \times h_k(M, M - \{x\}) \rightarrow (U \cap V) \times h_k(M, M - \{y\})$$

are continuous.

Let  $z \in U \cap V$ , and choose  $W$  such that  $z \in W \subset U \cap V$  and  $r_w^W$  is an isomorphism for each  $w \in W$ .

Consider the diagram

$$\begin{array}{ccccc} h_k(M, M - x) & \xleftarrow{r_x^U} & h_k(M, M - U) & \xrightarrow{r_w^U} & h_k(M, M - w) \\ & & \downarrow r_W^U & \nearrow r_w^W & \uparrow r_w^V \\ & & h_k(M, M - W) & \xleftarrow{r_W^V} & h_k(M, M - V) \\ & & & & \downarrow r_y^V \\ & & & & h_k(M, M - y) \end{array}$$

Let  $\varphi_{x,U,p}: h_k(M, M - x) \rightarrow \omega^{-1}(p)$  be defined by

$$\varphi_{x,U,p}(y) = \varphi_{x,U}(p, y).$$

Then for  $w \in U \cap V$ , we have

$$\varphi_{x,U,w}^{-1} \varphi_{y,V,w} = r_y^V (r_W^V)^{-1} (r_w^W)^{-1} r_w^W r_W^U (r_x^U)^{-1} = r_y^V (r_W^V)^{-1} r_W^U r_x^U$$

Firstly, this coincides with the operation of an element of the coefficient group  $G$  since it is an isomorphism  $G \rightarrow G$ , and secondly, note that this does not depend on  $w$ , so the map

$$g_{x,U,y,V}: U \cap V \rightarrow G$$

defined by  $g_{x,U,y,V}(p) = \varphi_{x,U,p}^{-1} \varphi_{y,V,p}$  is constant, hence continuous.

Thus  $\omega$  is indeed a covering map.

But even moreso, the fibers are groups, so for  $A \subset M$ , denote by  $\Gamma(A)$  the set of continuous sections over  $A$  of  $\omega$ . If  $s$  and  $t$  are section, we can define  $(s + t)(a) = s(a) + t(a)$ . Then  $s + t$  is again continuous, hence  $\Gamma(A)$  is an abelian group.

Denote by  $\Gamma_c(A) \subset \Gamma(A)$  the subgroup of sections with compact support, i.e., the sections which have values 0 in the fiber away from a compact set.

**Proposition 1.5.** *Let  $z \in h_k(M, M - U)$ . Then  $y \mapsto r_y^U z \in h_k(M, M - y) \subset h_k(M, M - \bullet)$  is a continuous section of  $\omega$  over  $U$ .*

*Proof.* The map  $U \rightarrow U \times G$  by  $y \mapsto (y, r_x^U z)$  is constant in the second coordinate, hence clearly continuous. Now composing with  $\varphi_{x,U}$  gives us the section in question.  $\square$

### 1.0.2. Local Homology in close-by points.

**Lemma 1.6.** *Let  $z, z'$  be cycles in  $\Delta_n(M, M - x; G)$ . Then a neighborhood  $V$  of  $x$  exists such that  $z, z'$  are cycles in  $\Delta_n(M, M - p; G)$  for all  $p \in V$ . If the homology classes of  $z, z'$  agree at  $x$ , i.e.,  $[z]_x = [z']_x \in H_n(M, M - x; G)$ , then they agree at all points  $q$  in a neighborhood  $V' \subset V$ .*

*Remark.* Hence  $H_n(M, M-x; G) \cong \lim_{\rightarrow} H_n(M, M-U; G)$  taken over neighborhoods of  $U$  containing  $x$  with maps the inclusions (We will introduce what this means later).

*Proof.* The chains  $\partial z, \partial z'$  are finite linear combinations of simplices  $\sigma$  with  $\text{im } \sigma \subset M - x$ . Since  $\text{im } \sigma$  is compact, there is a neighborhood  $V_\sigma$  of  $P$  such that  $\text{im } \sigma \subset M - V_\sigma$ . Using finiteness,  $V = \bigcap_\sigma V_\sigma$  is then an open neighborhood of  $x$  such that  $\partial z, \partial z' \in \Delta_n(M, M - V; G)$ . If  $[z]_x = [z']_x$ , then there exists a chain  $\partial c$  such that  $z - z' - \partial c \in \Delta_n(M - x; G)$ . So as we just saw, there exists a neighborhood  $V'$  of  $x$  such that  $z - z' - \partial c \in \Delta_n(M - V'; G)$ , and we may take  $V' \subset V$ . Thus for all  $q \in V'$ ,  $z - z' - \partial c \in \Delta_n(M - q; G)$ .  $\square$

1.0.3. *The topological situation - another perspective.*

**Proposition 1.7.** *We take the same orientation bundle as before:*

$$\omega: H_n(M, M - \bullet; G) \rightarrow M.$$

*For the topology on  $H_n(M, M - \bullet; G)$ , we consider pairs  $(V, z)$  where  $V$  is an open subset of  $M$  and  $z \in Z_n(M, M - V; G)$  is a cycle. Then define*

$$V_z = \{[z]_x \in H_n(M, M - x; G) \mid x \in V\}.$$

*The collections of all such  $V_z$  is then the base of the topology on  $H_n(M, M - \bullet; G)$ . With respect to this topology, the map  $\omega$  is a covering map. Furthermore, the maps  $(u, v) \mapsto u \pm v$  of  $D = \{(u, v) \in H_n(M, M - \bullet; G) \times H_n(M, M - \bullet; G) \mid \omega u = \omega v\}$  into  $H_n(M, M - \bullet; G)$  is continuous. Furthermore, the map*

$$\beta: H_n(M, M - \bullet; \mathbb{Z}) \rightarrow \mathbb{Z}, \quad \beta(u) = \|u\|$$

*is continuous, i.e., locally constant. Hence*

$$\tilde{M} = \tilde{M}(0) \oplus \tilde{M}(1) \oplus \tilde{M}(2) \oplus \dots$$

*where  $\tilde{M} = H_n(M, M - \bullet)$  and  $\tilde{M}(n) = \beta^{-1}(n)$ . The restricted maps  $\omega|_{\tilde{M}(n)}: \tilde{M}(n) \rightarrow M$  are covering maps.*

*Proof.* Let  $u \in H_n(M, M - \bullet; G)$  lies in some  $V_z$  as defined earlier: if  $z \in Z_n(M, M - x; G)$  represents  $u$ , then by Lemma 1.6, there exists an open neighborhood  $V$  of  $x$ , such that  $z \in Z_n(M, M - V; G)$ , hence  $u = [z]_x \in V_z$  by definition.

Now if  $u \in V'_z \cap V''_z$ , then by definition,  $u = [z']_x = [z'']_x$ , so by Lemma 1.6, there exists some neighborhood  $V \subset V' \cap V''$  such that  $[z']_p = [z'']_p$  for all  $p \in V$ , so for a representative  $z$  (for example, either  $z'$  or  $z''$ ), we have  $[z]_p = [z']_p = [z'']_p$  for all  $p \in V$ , so  $u \in V_z \subset V'_z \cap V''_z$ . Thus the set of all  $V_z$  is a basis.

Next, we show that  $\omega$  is a local homeomorphism. First, it maps  $V_z$  onto  $V$  bijectively by construction, hence  $\omega$  is open and locally bijective. It remains to show continuity. If  $W$  is an open neighborhood of  $x = \omega(u)$ , then  $u$  lies in some  $V_z$ , and hence  $(V \cap W)_z$  is a neighborhood of  $u$  which maps into  $W$  under  $\omega$ . Hence  $\omega$  is continuous.

Next, the map  $(u, u') \mapsto u \pm u'$  takes  $D \cap (V_z \times V_{z'})$  homeomorphically onto  $V_{z \pm z'}$ . We just saw that  $D \cap (V_z \times V_{z'}) \cong V_z \cong V \cong V_{z \pm z'}$ , which takes  $(u, u') \mapsto u \pm u'$ . Thus it is, in particular, continuous.

Lastly, we must show that  $\beta$  is locally constant and that  $\omega$  is a covering map.

Firstly, given  $x \in M$ , let  $V$  be the interior of some closed ball around  $x$ . Since  $r_x^V$  is an isomorphism, we have that, for  $z \in Z_n(M, M - V; \mathbb{Z})$ ,  $[z]_p = r_p^V [z]$  for each  $p \in V$ , so  $\beta([z]_p) = \|[z]_p\| = \|r_p^V [z]\| = \|[z]\|$ , hence  $\beta$  is independent of  $p$  in  $V$ , thus constant on  $V_z$ .

*Note.* Importantly, the norm is in a sense, the best we can do in the general situation because we only know that  $r_p^V$  is an isomorphism, *not* the identity. It could swap signs, in particular. We will see that this failure is at the heart of the notion of orientability.

Lastly, if  $[z]$  is a generator of  $H_n(M, M - V; \mathbb{Z}) \cong \mathbb{Z}$ , then  $\omega^{-1}(V) = \bigcup_{g \in G} V_{z \otimes g}$  is a decomposition into disjoint open sets  $V_{z \otimes g}$ , each of which map homeomorphically onto  $V$ , so  $\omega$  and each  $\omega|_{\tilde{M}(n)}$  is a covering map.  $\square$

**1.1. Homological Orientation.** If we specify to singular homology with coefficient group  $R$ , and again let  $M$  be an  $n$ -manifold and  $A \subset M$ , then we can define an orientation along  $A$  as follows

**Definition 1.8** ( $R$ -orientation of  $M$  along  $A$ ). An  $R$ -orientation of  $M$  along  $A$  is a section  $s \in \Gamma(A; R)$  of  $\omega: H_n(M, M - \bullet; R) \rightarrow M$  such that  $s(a) \in H_n(M, M - a; R) \cong R$  is a generator for each  $a \in A$ .

I.e., it is a section  $s$  such that  $\beta \circ s(x) = 1$  for all  $x \in A$ .

Thus  $s$  glues together the local orientations in a continuous manner.

When  $A = M$ , we call  $s$  an  $R$ -orientation of  $M$ .

*Note.* If  $s$  is a nowhere vanishing section, then  $a \mapsto \frac{s(a)}{\|s(a)\|}$  is an orientation.

**Definition 1.9** (Orientation covering). Let  $\text{Ori}(M) \subset H_n(M, M - \bullet; \mathbb{Z})$  be the subset of all generators of all fibers. Then the restriction  $\text{Ori}(M) \rightarrow M$  of  $\omega$  gives a 2-fold covering of  $M$ , called the *orientation covering* of  $M$ .

**Proposition 1.10.** *The following are equivalent:*

- (1)  $M$  is orientable
- (2)  $M$  is orientable along compact subsets.
- (3) The orientation covering is a trivial 2-fold covering map.
- (4) The covering  $\omega: H_n(M, M - \bullet; \mathbb{Z}) \rightarrow M$  is a trivial covering map.

*Proof.* (1)  $\implies$  (2) is a subcase.

(2)  $\implies$  (3). The orientation covering is trivial if and only if the covering over each component is trivial, so we may assume that  $M$  is connected. Now, if a 2-fold covering  $\tilde{M} \rightarrow M$  is trivial, then  $\tilde{M}$  splits as  $M \times \{p, q\}$ , and so  $\tilde{M}$  cannot be connected. Conversely, if  $\tilde{M}$  is not connected, then the covering restricted to each component must be a covering map, so the covering splits as a trivial covering.

Suppose then that  $\text{Ori}(M) \rightarrow M$  is non-trivial. Since  $\text{Ori}(M)$  is then connected, we can choose a path  $\gamma$  in  $\text{Ori}(M)$  between two points of a given fiber. The image  $S$  of such a path is compact and connected, and the covering is non-trivial over  $S$ , so by assumption (2), the orientation covering has a section  $s$  over  $S$ , but then  $\gamma(0) = s(\omega(\gamma(0))) = s(\omega(\gamma(1))) = \gamma(1)$ , which gives a contradiction.

(3)  $\implies$  (4).

Let  $s: M \rightarrow \text{Ori}(M) \cong M \times \{-1, 1\}$  be the section  $m \mapsto (m, 1)$ .

Now define a map  $\varphi: M \times \mathbb{Z} \rightarrow H_n(M, M - \bullet; \mathbb{Z})$  by  $\varphi(m, k) = ks(m)$ . This is a bijective map by assumption on  $s$  being a section. It is furthermore continuous since  $s$  is continuous and since fiber-wise operations in  $H_n(M, M - \bullet; \mathbb{Z})$  is continuous. Furthermore, it is also a morphism between coverings since it commutes with the projections:  $\pi_M = \omega \circ \varphi$ .

Lastly, one must show that it also has a continuous inverse. For this, we may take an open basis set in  $M \times \mathbb{Z}$  - say  $U \times \{k\}$ , where  $U$  is a convex subset of  $\mathbb{R}^n \subset M$ . Since  $\varphi$  is bijective, we obtain that  $\varphi(U \times \{k\}) = ks(U) = U_\alpha$  if we choose  $\alpha$  to be the element in  $H_n(M, M - U) \cong \mathbb{Z}$  which maps to  $k$  under  $r_{x,U}$  for  $x \in U$ . And by assumption,  $U_\alpha$  is a basis open set for the topology on  $H_n(M, M - \bullet; \mathbb{Z})$ .

Hence  $\varphi$  is a homeomorphism, and even an isomorphism of covering spaces in the sense that  $\pi_M = \omega \circ \varphi$ .

*Note.* We could also say that it is trivial since every point is in the image of some section.

(4)  $\implies$  (1) : If  $\omega$  is trivial, then it has a section with constant value in the set of generators.

□

**1.2. Homology in the Dimension of the Manifold.** Let  $M$  be an  $n$ -manifold and  $A \subset M$  a closed subset. We will in this section use singular homology with coefficients in an abelian group  $G$ .

**Proposition 1.11.** *For each  $\alpha \in H_n(M, M - A; G)$ , the section*

$$J^A(\alpha): A \rightarrow H_n(M, M - \bullet; G), \quad x \mapsto r_x^A(\alpha)$$

*of  $\omega$  over  $A$  is continuous and has compact support.*

*Proof.* Choose a representative  $c \in \Delta_n(M; G)$  representing  $\alpha$ . There exists a compact set  $K$  such that  $c$  is contained in  $K$ . Suppose  $A - K$  is nonempty, and let  $x \in A - K$ . Then the image of  $c$  under

$$\Delta_n(K; G) \rightarrow \Delta_n(M; G) \rightarrow \Delta_n(M, K; G) \rightarrow \Delta_n(M, M - x; G)$$

is zero since  $K \subset M - x$ . Since this image represents  $r_x^A$ , the support of  $J^A(\alpha)$  is contained in  $A \cap K$  which is compact.

If  $A - K$  is empty,  $K$  contains  $A$ , and then the support of  $J^A(\alpha)$  is a closed subset of a compact space, hence compact.

The continuity follows from the more general case of Proposition 1.5. □

Thus we obtain a homomorphism

$$J^A: H_n(M, M - A; G) \rightarrow \Gamma_c(A; G), \quad \alpha \mapsto (x \mapsto r_x^A(\alpha))$$

which is also natural with respect to inclusions: i.e., for  $A \subset A' \subset M$ ,

$$\begin{array}{ccc} H_n(M, M - A'; G) & \xrightarrow{J^{A'}} & \Gamma_c(A'; G) \\ \downarrow i_* & & \downarrow \rho \\ H_n(M, M - A; G) & \xrightarrow{J^A} & \Gamma_c(A; G) \end{array}$$

commutes.

### 1.3. Direct Limits.

**Definition 1.12** (Directed set). A *directed set*  $D$  is a partially ordered set such that, for any two elements  $\alpha$  and  $\beta$  of  $D$ , there is a  $\tau \in D$  with  $\tau \geq \alpha$  and  $\tau \geq \beta$ .

**Definition 1.13.** Let  $D$  be a directed set and  $G_\alpha$  an abelian group defined for each  $\alpha \in D$ . Suppose we are given homomorphisms  $f_{\beta,\alpha}: G_\alpha \rightarrow G_\beta$  for each  $\beta > \alpha$  in  $D$ . Assume that for all  $\gamma > \beta > \alpha$  in  $D$ , we have  $f_{\gamma,\beta}f_{\beta,\alpha} = f_{\gamma,\alpha}$ . Such a system is called a *direct system* of abelian groups. Then  $G = \lim_{\rightarrow} G_\alpha$  is defined to be the quotient group of the direct sum  $G = \bigoplus G_\alpha$  modulo the relations  $f_{\beta,\alpha}(g) \sim g$  for all  $g \in G_\alpha$  and all  $\beta > \alpha$ .

*Note.* Hence the direct limit is just the colimit of the direct system.

The inclusions  $G_\alpha \hookrightarrow \bigoplus G_\alpha$  induce homomorphisms  $i_\alpha: G_\alpha \rightarrow \lim_{\rightarrow} G_\alpha$  and  $i_\beta \circ f_{\beta,\alpha} = i_\alpha$ . Moreover, for any  $g \in G$ , there is a  $g_\alpha \in G_\alpha$  for some  $\alpha$  such that  $g = i_\alpha(g_\alpha)$ . Also, for any index  $\alpha \in D$ , and element  $g_\alpha \in G_\alpha$ , we have  $i_\alpha(g_\alpha) = 0$  if and only if there exists a  $\beta \geq \alpha$  such that  $f_{\beta,\alpha}(g_\alpha) = 0$ . These properties characterize the direct limit:

**Proposition 1.14.** Suppose we are given an abelian group  $A$  with homomorphisms  $h_\alpha: G_\alpha \rightarrow A$  such that the cocone commutes. Since  $\lim_{\rightarrow} G_\alpha$  is the colimit, we have a unique induced homomorphism  $h: \lim_{\rightarrow} G_\alpha \rightarrow A$ . Then

- (1)  $\text{im } h = \{a \in A \mid a = h_\alpha(g) \text{ for some } g \text{ and } \alpha\} = \bigcup \text{im } h_\alpha$ .
- (2)  $\ker h = \{g \in \lim_{\rightarrow} G_\alpha \mid \exists \alpha \text{ and } g_\alpha \in G_\alpha : g = i_\alpha(g_\alpha) \text{ and } h_\alpha(g_\alpha) = 0\} = \bigcup i_\alpha(\ker h_\alpha)$ .

*Proof.* Define  $h(g_\alpha) = h_\alpha(g_\alpha)$ . Then if  $f_{\beta,\alpha}(g_\alpha) \sim g_\alpha$ , we have  $h(g_\alpha) = h_\alpha(g_\alpha) = h_\beta \circ f_{\beta,\alpha}(g_\alpha) = h_\beta(f_{\beta,\alpha}(g_\alpha))$ , so  $h$  respects the equivalence relations, thus it is well-defined.

Now property (1) is clear by the way we defined  $h$ .

As for (2), note that if  $g$  represents the equivalence class of  $g_\alpha$  and  $h(g) = 0$ , then  $h_\alpha(g_\alpha) = 0$  which is what (2) is saying.  $\square$

**Corollary 1.15.** In the situation of Proposition 1.14,  $h: \lim_{\rightarrow} G_\alpha \rightarrow A$  is an isomorphism if and only if the following two statements hold true:

- (1)  $\forall a \in A, \exists \alpha \in D \text{ and } g_\alpha \in G_\alpha : h_\alpha(g_\alpha) = a$ , and
- (2) if  $h_\alpha(g_\alpha) = 0$  then  $\exists \beta > \alpha : f_{\beta,\alpha}(g_\alpha) = 0$ .

**Theorem 1.16.** The direct limit is an exact functor. So if we have direct systems  $\{A'_\alpha\}, \{A_\alpha\}$  and  $\{A''_\alpha\}$  based on the same directed set, and if we have an exact sequence  $A'_\alpha \rightarrow A_\alpha \rightarrow A''_\alpha$  for each  $\alpha$ , where the maps commute with the ones defining the direct systems, then the induced sequence

$$\lim_{\rightarrow} A'_\alpha \rightarrow \lim_{\rightarrow} A_\alpha \rightarrow \lim_{\rightarrow} A''_\alpha$$

is exact.

*Proof.* We have the following diagram, where all maps commute.

$$\begin{array}{ccccc} A'_\beta & \longrightarrow & A_\beta & \longrightarrow & A''_\beta \\ \downarrow & & \downarrow & & \downarrow \\ \lim_{\rightarrow} A'_\alpha & \longrightarrow & \lim_{\rightarrow} A_\alpha & \longrightarrow & \lim_{\rightarrow} A''_\alpha \end{array}$$

Suppose  $a \in \lim_{\rightarrow} A_*$  is mapped to zero in  $\lim_{\rightarrow} A''_*$ . Then there exists  $g \in \lim_{\rightarrow} A_\alpha$  such that there exists  $\beta$  and  $g_\beta \in A_\beta$  such that  $g = i_\beta(g_\beta)$  and  $h_\beta(g_\beta) = 0$ .

Recall here that  $h_\beta$  is a homomorphism  $A_\beta \rightarrow \lim_{\rightarrow} A''_*$  and  $i_\beta$  is the inclusion  $G_\beta \rightarrow \lim_{\rightarrow} G_\alpha$ .

By commutativity of the diagram, there then exists  $k_\beta \in A'_\beta$  such that

$$i_\beta(d_\beta(k_\beta)) = d_{\lim_{\rightarrow}} i'_\beta(k_\beta). \text{ Hence the kernel is contained in the image.}$$

Now suppose let  $\tilde{k} = d_{\lim_{\rightarrow}}(k) \in \lim_{\rightarrow} A_*$ .

Then  $\tilde{k} = i_\beta(d(\bar{k})) = d_{\lim_{\rightarrow}} i'_\beta(\bar{k})$  for some  $\bar{k} \in A'_\beta$ .

But now

$$d_{\lim_{\rightarrow}}(\tilde{k}) = d_{\lim_{\rightarrow}} i_\beta(d(\bar{k})) = i''_\beta d(d(\bar{k})) = i''_\beta(0) = 0.$$

□

**Theorem 1.17.** Suppose we are given two directed sets  $D$  and  $E$ . Define an order on  $D \times E$  by  $(\alpha, \beta) \geq (\alpha', \beta')$  if and only if  $\alpha \geq \alpha'$  and  $\beta \geq \beta'$ . Suppose  $G_{\alpha, \beta}$  is a direct system based on  $D \times E$ . Then the maps  $G_{\alpha, \beta} \rightarrow \lim_{\rightarrow, \beta} G_{\alpha, \beta} \rightarrow \lim_{\rightarrow, \alpha} (\lim_{\rightarrow, \beta} G_{\alpha, \beta})$  induce an isomorphism

$$\lim_{\rightarrow, \alpha, \beta} G_{\alpha, \beta} \xrightarrow{\cong} \lim_{\rightarrow, \alpha} \left( \lim_{\rightarrow, \beta} G_{\alpha, \beta} \right).$$

*Proof.*

□

**Proposition 1.18.** (1) For  $A \supset B$  both closed, the following diagram commutes:

$$\begin{array}{ccc} H_n(M, M - A; G) & \longrightarrow & H_n(M, M - B; G) \\ \downarrow J^A & & \downarrow J^B \\ \Gamma_c(A, H_n(M, M - \bullet; G)) & \longrightarrow & \Gamma_c(B, H_n(M, M - \bullet; G)) \end{array}$$

(2) For  $A, B \subset M$  both closed, the sequence

$$\begin{aligned} 0 \rightarrow \Gamma_c(A \cup B, H_n(M, M - \bullet; G)) &\xrightarrow{h} \Gamma_c(A, H_n(M, M - \bullet; G)) \oplus \Gamma_c(B, H_n(M, M - \bullet; G)) \\ &\xrightarrow{k} \Gamma_c(A \cap B, H_n(M, M - \bullet; G)) \end{aligned}$$

is exact, where  $h$  is the sum of restrictions and  $k$  is the difference of restrictions.

(3) If  $A_1 \supset A_2 \supset A_3 \supset \dots$  are all compact and  $A \cap A_i$ , then the restriction homomorphisms  $\Gamma(A_i, H_n(M, M - \bullet; G)) \rightarrow \Gamma(A, H_n(M, M - \bullet; G))$  induce an isomorphism

$$\lim_{\rightarrow} \Gamma(A_i, H_n(M, M - \bullet; G)) \xrightarrow{\cong} \Gamma(A, H_n(M, M - \bullet; G))$$

*Proof.* (1) Let  $\alpha \in H_n(M, M - A; G)$ , and denote by  $\iota$  the inclusion  $(M, M - A) \hookrightarrow (M, M - B)$ . Then  $\iota_* = r_B^A$ , so  $J^B(r_B^A(\alpha))(x) = r_x^B(r_B^A(\alpha))$ . On the other hand,  $J^A(\alpha)|_B(x) = J^A(\alpha)(x) = r_x^A(\alpha)$ . Now, from the composition

$$(M, M - A) \hookrightarrow (M, M - B) \hookrightarrow (M, M - x)$$

we obtain by taking homology, that  $r_x^A = r_x^B r_B^A$ , which gives the result.

(2) Firstly, a section that is zero on both  $A$  and  $B$  is then also zero on  $A \cup B$ , which gives the injective part of  $h$ . Now, suppose  $s - t$  is the zero section over

$A \cap B$  for  $s$  a section over  $A$  and  $t$  a section over  $B$ . Then  $s$  and  $t$  agree on  $A \cap B$ , meaning that  $s \cup t$  is well-defined and continuous, where  $s \cup t$  is  $s$  on  $A$  and  $t$  on  $B$ , and  $h(s \cup t) = (s, t)$ . Likewise, if  $g$  is a section over  $A \cup B$ , then  $k \circ h(g) = (g|_A)|_{A \cap B} - (g|_B)|_{A \cap B} = g|_{A \cap B} - g|_{A \cap B}$  is the zero section.

(3)

□

**Theorem 1.19.** *Let  $A \subset M$  be closed. Then*

- (1)  $H_i(M, M - A; G) = 0$  for  $i > n$ .
- (2)  $J^A: H_n(M, M - A, G) \rightarrow \Gamma_c(A, H_n(M, M - \bullet; G))$  is an isomorphism.

**Lemma 1.20** (The Bootstrap Lemma). *Let  $P_M(A)$  be a statement about compact sets  $A$  in a given  $n$ -manifold  $M^n$ . If (i), (ii), (iii) hold, then  $P_M(A)$  is true for all compact  $A$  in  $M^n$ .*

*If  $M^n$  is separable metric, and  $P_M(A)$  is defined for all closed sets  $A$ , and if (i), (ii), (iii), (iv) hold, then  $P_M(A)$  is true for all closed sets  $A$  in  $M$ .*

*For general  $M^n$ , if  $P_M(A)$  is defined for all closed sets  $A$  in  $M$ , for all  $M^n$ , and if all five statement (i) – (v) hold for all  $M^n$ , then  $P_M(A)$  is true for all closed  $A \subset M$  and all  $M^n$ .*

Now note that for a given abelian group  $G$  and  $g \in G$ , the following maps are natural in  $A \subset M$  (closed):

$$H_n(M, M - A) \cong H_n(M, M - A) \otimes \mathbb{Z} \rightarrow H_n(M, M - A) \otimes G \rightarrow H_n(M, M - A; G)$$

where the middle map is induced by the homomorphism  $\mathbb{Z} \rightarrow G$  taking 1 to  $g$ .

In particular, this induces a map

$$H_n(M, M - \bullet) \rightarrow H_n(M, M - \bullet; G)$$

**Lemma 1.21.** *The sections  $\Gamma(A; G)$  of  $\omega$  over  $A$  correspond bijectively to continuous maps  $\lambda: \text{Ori}(M)|_A \rightarrow G$  with the property  $\lambda \circ t = -\lambda$ , where  $t$  acts on  $G$  as multiplication by  $-1$ .*

*Proof.* We may assume  $A$  is connected.

Let  $s \in \Gamma(A; G)$  be a section of  $\omega$  over  $A$ . That is,  $w \circ s = \text{id}_A$ , and  $s$  is a map  $A \rightarrow H_n(M, M - \bullet; G)$ . We can define an associated map  $\lambda_s: \text{Ori}(M)|_A \rightarrow G$  by sending a generator in the fiber  $x \in A$  to  $s(x) \in H_n(M, M - \{x\}; G) \cong G$ . If one chose the other generator, one would get the negative of the above map, so we have the relation  $\lambda_s \circ t = -\lambda_s$ . Subject to this relation, we obtain a well-defined map  $\Gamma(A; G) \rightarrow S \subset \text{Hom}(\text{Ori}(M)|_A, G)$ , where  $S$  is the subset for which  $\lambda \circ t = -\lambda$  holds. This map is certainly injective, since the image tells us precisely the value of  $s$  at any point in  $A$ .

It is furthermore surjective, since if  $\text{Ori}(M)|_A$  is connected, then  $S$  can only consist of the zero section, and if it is not connected, it consists of a map on two components on which it is constant, and the relation  $\lambda \circ t = -\lambda$  then determines that it must be the required values to constitute the induced map of a section. □

check

**Theorem 1.22.** *Suppose  $A \subset M$  is a closed connected subset. Then*

- (1)  $H_n(M, M - A; G) = 0$  if  $A$  is not compact.
- (2)  $H_n(M, M - A; G) \cong G$  if  $M$  is  $R$ -orientable along  $A$  and  $A$  is compact. Moreover,  $H_n(M, M - A; G) \rightarrow H_n(M, M - x; G)$  is an isomorphism for each  $x \in A$ .



- (3)  $H_n(M, M - A; G) \cong {}_2G = \{g \in G \mid 2g = 0\}$  if  $M$  is not orientable along  $A$  and  $A$  is compact.

*Proof.* (1) By Lemma 7.1, a section in  $\Gamma(A; G)$  is determined by its value at a single point. By the existence of the zero section, if a section is non-zero at any point, then it is non-zero at every point. Therefore, there do not exist non-zero sections with compact support over a non-compact  $A$ , so by Theorem 1.19,  $H_n(M, M - A; G) \cong \Gamma_c(A; G) \cong 0$ .

(2) Since  $A$  is compact,  $H_n(M, M - A; G) \cong \Gamma_c(A; G) = \Gamma(A; G)$ . A section is again determined by a single point. Recall now the commutative diagram

$$\begin{array}{ccc} H_n(M, M - A; G) & \xrightarrow{\cong} & \Gamma(A; G) \\ \downarrow r_x^A & & \downarrow b \\ H_n(M, M - x; G) & \xrightarrow{\cong} & \Gamma(\{x\}; G) \end{array}$$

from Proposition 1.18, the horizontal isomorphisms following from Theorem 1.19. If  $M$  is orientable along  $A$ , there by definition exists in  $\Gamma(A; G)$  an element such that its value at  $x$  is a generator. Hence  $b$  is an isomorphism, and therefore also  $r_x^A$  is an isomorphism.

(3) By Lemma 1.21, a section in  $\Gamma(A; G)$  corresponds to a continuous map  $\lambda: \text{Ori}(M)|_A \rightarrow G$  with  $\lambda t = -\lambda$ . If  $M$  is not orientable along  $A$ , then  $\text{Ori}(M)|_A$  is connected and therefore  $\lambda$  is constant as  $G$  has the discrete topology. The relation  $\lambda t = -\lambda$  shows that  $\lambda$  is in  ${}_2G$ . Now by the commutative diagram from part (2), note that since  $\lambda$  must be constant, firstly  $\Gamma(A; G) \cong {}_2G$ , and secondly,  $b$  becomes injective, so  $r_x^A: H_n(M, M - A; G) \rightarrow H_n(M, M - x; G) \cong G$  is injective and has image  ${}_2G$ , so the Hom term vanishes.  $\square$

**Proposition 1.23.** *Let  $M$  be an  $n$ -manifold and  $A \subset M$  be a closed connected subset. Then the torsion subgroup of  $H_{n-1}(M, M - A; \mathbb{Z})$  is of order 2 if  $A$  is compact and  $M$  non-orientable along  $A$ , and is 0 otherwise.*

*Proof.* By UCT for homology,

$$\begin{aligned} \mathbb{Z}/2 \cong {}_2\mathbb{Z}/2 \cong H_n(M, M - A; \mathbb{Z}/2) &\cong H_n(M, M - A) \otimes \mathbb{Z}/2 \oplus \text{Tor}_1(H_{n-1}(M, M - A), \mathbb{Z}/2) \\ &\cong \text{Tor}_1(H_{n-1}(M, M - A), \mathbb{Z}/2) \\ &\cong \{g \in H_{n-1}(M, M - A) \mid 2g = 0\}. \end{aligned}$$

where  $H_n(M, M - A) \cong {}_2\mathbb{Z} = 0$ , and  $H_n(M, M - A; \mathbb{Z}/2) \cong {}_2\mathbb{Z}/2 \cong \mathbb{Z}/2$  both follow from Theorem 1.22.

To see that this is the whole torsions subgroup, note that for odd  $k$ ,

$$\text{Tor}_1(H_{n-1}(M, M - A), \mathbb{Z}/k) \cong H_n(M, M - A; \mathbb{Z}/k) \cong {}_2\mathbb{Z}/k \cong 0$$

When  $M$  is orientable along  $A$  and  $A$  is compact, we simply obtain

$$0 \rightarrow H_n(M, M - A) \otimes \mathbb{Z}/n \rightarrow H_n(M, M - A; \mathbb{Z}/n) \rightarrow \text{Tor}_1(H_{n-1}(M, M - A), \mathbb{Z}/n) \rightarrow 0$$

and since  $H_n(M, M - A) \cong \mathbb{Z}$  and  $H_n(M, M - A; \mathbb{Z}/n) \cong \mathbb{Z}/n$  by Theorem 1.22, we find that  $\text{Tor}_1$  vanishes for all  $n$ .

If  $A$  is non-compact, then Theorem 1.22 gives that  $\text{Tor}_1$  trivially vanishes for all terms.

□

#### 1.4. Fundamental Class.

**Theorem 1.24.** *Let  $M$  be a compact connected  $n$ -manifold. Then one of the following assertions holds:*

- (1)  $M$  is orientable,  $H_n(M) \cong \mathbb{Z}$ , and for each  $x \in M$ , the restriction  $H_n(M) \rightarrow H_n(M, M - x)$  is an isomorphism.
- (2)  $M$  is non-orientable and  $H_n(M) = 0$ .

*Proof.* Special case of Theorem 1.22. □

Under the hypothesis of Theorem 1.24, the orientations of  $M$  correspond to the generators of  $H_n(M)$ . Such a generator will be called a *fundamental class* or *homological class/orientation* of the orientable manifold.

**Definition 1.25** (Degree). Let  $M$  and  $N$  be compact oriented  $n$ -manifolds. Let  $N$  be connected and suppose  $M$  has components  $M_1, \dots, M_r$ . Then we have fundamental classes  $z(M_j)$  for each  $M_j$  and  $z(M) \in H_n(M) \cong \bigoplus_j H_n(M_j)$  is the sum of the  $z(M_j)$ . Now, since  $H_n(N) \cong \langle z(N) \rangle \cong \mathbb{Z}$ , we obtain that there exists a *degree*  $d(f) \in \mathbb{Z}$  such that  $f_* z(M) = d(f) z(N)$ .

**Lemma 1.26** (Properties). (1) *The degree is a homotopy invariant.*

- (2)  $d(f \circ g) = d(f)d(g)$ .
- (3) *A homotopy equivalence has degree  $\pm 1$ .*
- (4) *If  $M = M_1 \sqcup M_2$ , then  $d(f) = d(f|_{M_1}) + d(f|_{M_2})$ .*
- (5) *If we pass in  $M$  or  $N$  to the opposite orientation, then the degree changes the sign.*

1.4.1. *Computations of degrees.* As usual, we can compute degrees in terms of local data of a map.

Let  $M$  and  $N$  be connected and set  $K = f^{-1}(p)$ . Let  $U$  be an open neighborhood of  $K$  in  $M$ . Then in particular  $M - U = \overline{M - U} \subset \text{int}(M - A) = M - A$ , so excision gives the bottom left isomorphism in the following diagram, and the top right isomorphism follows from Theorem 1.24:

$$\begin{array}{ccccc}
 z(M) \in & H_n(M) & \xrightarrow{f_*} & H_n(M) & \ni z(N) \\
 \downarrow & \downarrow & & \downarrow \cong & \downarrow \\
 & H_n(M, M - K) & \xrightarrow{f_*} & H_n(N, N - p) & \\
 & \uparrow i_* & & \uparrow = & \\
 z(U, K) \in & H_n(U, U - K) & \xrightarrow{f_*^U} & H_n(N, N - p) & \ni z(N, p)
 \end{array}$$

From the outer rectangle, we get  $f_*^U z(U, K) = d(f) z(N, p)$ , where  $z(N, p)$  and  $z(U, K)$  are the images of  $z(N)$  and  $z(M)$  under the indicated maps.

We want to show additivity of degree as in the case for spheres.

So suppose  $K$  is finite, and choose  $U = \bigcup_{x \in K} U_x$  where the  $U_x$  are pair-wise disjoint open neighborhoods of  $x$ . Then

$$\bigoplus_{x \in K} H_n(U_x, U_x - x) \cong H_n(U, U - K), \quad H_n(U_x, U_x - x) \cong \mathbb{Z}.$$

The image  $z(U_x, x)$  of  $z(M)$  is a generator: it is the image under the following isomorphisms

$$H_n(M) \xrightarrow{\cong} H_n(M, M - x) \xrightarrow{\cong} H_n(U_x, U_x - x)$$

where the first follows from Theorem 1.24 and the second from excision. The local degree  $d(f, x)$  is determined by  $f_* z(U_x, x) = d(f, x) z(N, p)$ , and by additivity above, we have  $d(f) = \sum_{x \in K} d(f, x)$ .

**Proposition 1.27.** *Let  $M$  be a connected, oriented, closed  $n$ -manifold. Then there exists for each  $k \in \mathbb{Z}$  a map  $f: M^n \rightarrow S^n$  of degree  $k$ .*

*Remark.* If  $f$  is  $C^1$  in a neighborhood of  $x$ , then  $d(f, x)$  is the sign of the determinant of  $Dg(0)$  when  $Dg(x)$  is regular, where  $g$  is  $f$  in local coordinates that preserve local orientations. By this we mean that for  $\varphi: U_x \rightarrow \mathbb{R}^n$  centered at  $x$ ,  $\varphi_*: H_n(U_x, U_x - x) \rightarrow H_n(\mathbb{R}^n, \mathbb{R}^n - 0)$  sends  $z(U_x, x)$  to the standard generator. Such charts are called *positive* with respect to the given orientations.

*Proof.* If  $f: M \rightarrow S^n$  has degree  $a$  and  $g: S^n \rightarrow S^n$  degree  $b$ , then  $gf$  has degree  $ab$ . Since the proposition is true for  $M = S^n$ , it suffices to find  $f$  having degree  $\pm 1$ . Let  $\varphi: D^n \rightarrow M$  be an embedding. Then we have a map  $f: M \rightarrow D^n/S^{n-1}$  which is the inverse of  $\varphi$  on  $U = \varphi(\text{int } D^n)$  and sends  $M - U$  to the basepoint. This map has degree  $\pm 1$  as can be seen by choosing any neighborhood of  $x$  in the interior of  $U$  and looking at the determinant of the differential locally.  $\square$

### 1.5. Manifolds with Boundary.

**Definition 1.28.** For  $M$  an  $n$ -dimensional manifold with boundary, we call  $z \in H_n(M, \partial M)$  a *fundamental class* if for each  $x \in M - \partial M$ , the restriction of  $z$  is a generator in  $H_n(M, M - x)$ .

**Theorem 1.29.** *Let  $M$  be a compact connected  $n$ -manifold with non-empty boundary. Then one of the following assertions hold:*

- (1)  $H_n(M, \partial M) \cong \mathbb{Z}$ , and a generator of this group is a fundamental class. The image of a fundamental class under  $\partial: H_n(M, \partial M) \rightarrow H_{n-1}(\partial M)$  is a fundamental class. The interior  $M - \partial M$  is orientable.
- (2)  $H_n(M, \partial M) = 0$ , and  $M - \partial M$  is not orientable.

*Proof.* See [4, Thm 16.5.1]. We will follow that proof and only add a few extra words.

Let  $\kappa: [0, \infty) \times \partial M \rightarrow U$  be a collar of  $M$ , i.e., a homeomorphism onto an open neighborhood  $U$  of  $\partial M$  such that  $\kappa(0, x) = x$  for  $x \in \partial M$  (See Milnor's  $h$ -cobordism book for existence). For simplicity of notation, we identify  $U$  with  $[0, \infty) \times \partial M$  via  $\kappa$ ; similarly, for subsets of  $U$ . In this sense,  $\partial M = 0 \times \partial M$ . For  $A = M - ([0, 1) \times \partial M) \subset M - \partial M$ , we have isomorphisms

$$H_n(M, \partial M) \cong H_n(M, [0, 1) \times \partial M) \cong H_n(M - \partial M, (0, 1) \times \partial M) \cong \Gamma(A).$$

The first one by homotopy equivalence, the second by excision, and the third using Theorem 1.19.

Since  $A$  is connected,  $\Gamma(A) \cong \mathbb{Z}$  or  $\Gamma(A) \cong 0$ . If  $\Gamma(A) \cong \mathbb{Z}$ , then  $M - \partial M$  is orientable along  $A$ .

Let now  $A_\varepsilon \cong A$  be the complement of  $[0, \varepsilon) \times \partial M$ . Since each compact subset of  $M - \partial M$  is contained in some such  $M_\varepsilon$  for small enough  $\varepsilon$ , we see that  $M - \partial M$  is orientable along all compact subsets, hence orientable by Proposition 1.10.

The isomorphism  $H_n(M - \partial M, (0, 1) \times \partial M) \cong \Gamma(A)$  from above says that there exists some  $z \in H_n(M - \partial M, (0, 1) \times \partial M)$  which restricts to a generator of  $H_n(M - \partial M, M - \partial M - x)$  for each  $x \in A$ . For the corresponding element  $z \in H_n(M, \partial M) \cong \mathbb{Z}$ , the same assertion holds for any  $x \in M - \partial M$  (simply shrink the collar to not contain  $x$ ). Lastly, we must show that  $\partial z$  is a fundamental class. Let  $x \in (0, 1) \times \partial M$ . Consider the diagram:

$$\begin{array}{ccccc}
 H_{n-1}(\partial M) & \xrightarrow{\cong} & H_{n-1}(\partial M \cup A, A) & \xleftarrow{\cong} & H_{n-1}(I \times \partial M, 1 \times \partial M) \\
 \partial \uparrow & & \cong \uparrow \partial & & \cong \uparrow \partial \\
 H_n(M, \partial M) & \longrightarrow & H_n(M, \partial M \cup A) & \xleftarrow{\cong} & H_n(I \times \partial M, \partial I \times \partial M) \\
 & \searrow & \downarrow & & \\
 & & H_n(M, M - x) & \xleftarrow{\cong} & H_n(I \times \partial M, I \times \partial M - x)
 \end{array}$$

Commutativity of the bottom left triangle tells us that the image of  $z$  under  $H_n(M, \partial M) \rightarrow H_n(M, \partial M \cup A)$  gives an element whose restriction gives a generator in  $H_n(M, M - x)$ , but then by commutativity of the bottom right square, we get that the restriction of  $z$  transferred over by the isomorphism to  $H_n(I \times \partial M, \partial I \times \partial M)$  is a generator of  $H_n(I \times \partial M, I \times \partial M - x)$  at each point in  $(0, 1) \times \partial M$ . Hence  $z$  yields a fundamental class in  $H_n(I \times \partial M, \partial I \times \partial M)$ .

But since  $z$  is a generator in  $H_n(I \times \partial M, \partial I \times \partial M)$ , the upper part shows that  $z$  is a generator in  $H_{n-1}(\partial M)$ , thus a fundamental class of  $\partial M$  since this characterizes fundamental classes.  $\square$

**Example 1.30.** Suppose that  $B: M \rightarrow \emptyset$  is a cobordism. We have the fundamental classes  $z(B) \in H_{n+1}(B, \partial B)$  and  $z(M) = \partial z_B \in H_n(M)$  (here we crucially made use of our result in Theorem 1.29). This is already a lot of information. Indeed, suppose  $f: M \rightarrow N$  is a map which has an extension to  $B: F: B \rightarrow N$ . Then the degree of  $f$  (if defined) is zero,  $d(f) = 0$ , for we have  $f_* z(M) = f_* \partial z(B) = F_* i_* \partial z(B) = 0$ , since  $i_* \partial = 0$  by the exactness of the homology sequence for the pair  $(B, M)$ .

We call maps  $f_\nu: M_\nu \rightarrow N$  *orientable bordant* if there exists a compact oriented cobordism  $B: M_1 \rightarrow M_2$  with orientable boundary  $\partial B = M_1 - M_2$  (meaning  $\partial z(B) = z(M_1) - z(M_2)$ ) and an extension  $F: B \rightarrow N$  of  $f_1 \sqcup f_2: M_1 \sqcup M_2 \rightarrow N$ . Under these assumptions, we have  $d(f_1) = d(f_2)$ . This fact is called the *bordism invariance* of the degree; it generalizes the homotopy invariance.

**Exercise 1.31.** If  $M^m$  and  $N^n$  are manifolds, then show that  $M \times N$  is orientable if and only if  $M$  and  $N$  are orientable.

*Proof.* We may assume that  $M$  and  $N$  are connected.

Define a map  $\mu: \tilde{M} \times \tilde{N} \rightarrow \tilde{M} \times \tilde{N}$  by

$$\mu(u, v) = u \times v \in H_{m+n}((M, M - x) \times (N, N - y)) = H_{m+n}(M \times N, M \times N - (x, y))$$

where  $\times$  is the cross product.

Note that  $\gamma^{M \times N} \circ \mu = \gamma^M \times \gamma^N$ . We want to use this map to transfer sections: if  $(s, t): M \times N \rightarrow \tilde{M} \times \tilde{N}$  are sections, then we want  $\mu \circ (s, t)$  to be a section. This requires us to show that  $\mu$  is continuous.

Let  $U, V$  be open neighborhoods of  $x$  and  $y$ , respectively, such that  $z \in Z_m(M, M - U)$  and  $w \in Z_n(N, N - V)$  represent  $u, v$ , respectively.

Recall the relative Eilenberg-Zilber chain homotopy equivalence for open sets:

$$\begin{aligned} \times : \Delta_*(X, U) \otimes \Delta_*(Y, V) &\rightarrow \Delta_*((X, U) \times (Y, V)) = \Delta_*(X \times Y, X \times V \cup U \times Y) \\ &= \Delta_*(X \times Y, X \times Y - U \times V) \end{aligned}$$

which takes  $z \otimes w$  to  $z \times w$  which represents  $u \times v$ . Let  $W_{z \times w}$  be a neighborhood of  $u \times v$ . We can shrink  $U$  and  $V$  such that  $U \times V \subset W$ . Then  $\mu$  takes  $U_z \times V_w$  into  $W_{z \times w}$ : for  $(p, q) \in U \times V$ ,

$$\mu\left(\left([z]_p, [w]_q\right)\right) = [z]_p \times [w]_q = [z \times w]_{(p, q)}.$$

Thus  $\mu$  is continuous. This gives a bilinear map

$$\Gamma A \times \Gamma B \rightarrow \Gamma(A \times B)$$

for  $A \subset M, B \subset N$ . Furthermore, the cross product takes a product of generators to a generator by the Künneth theorem, hence it maps a pair of orientations to an orientation which was what we wanted.

For the converse direction, we note that  $\mu$  also satisfies  $\beta^{M \times N} \mu(u, v) = \beta^M(v) \beta^N(v)$  since it is bilinear. Thus  $\mu$  restricts to a map

$$\mu| : \tilde{M}(1) \times \tilde{N}(1) \rightarrow \widetilde{M \times N}(1),$$

and for each point  $w \in \widetilde{M \times N}(1)$ , the preimage under  $\mu|$  has two points. Furthermore, since  $\gamma^{M \times N} \circ \mu = \gamma^M \times \gamma^N$  and  $\gamma$  is a local homeomorphism, we find that  $\mu$  restricts to a local homeomorphism, hence  $\mu$  restricts to a two-sheeted covering map.

If either  $M$  or  $N$  is orientable, then  $\tilde{M}(1)$  or  $\tilde{N}(1)$  splits as  $M \times \{-1, 1\}$  or  $N \times \{-1, 1\}$ , respectively, and so the LHS becomes disconnected, and the restriction to each component is a covering map, hence a homeomorphism, so the covering map is trivial.

Conversely, if the covering map is trivial, then there is a map  $q : \tilde{M}(1) \times \tilde{N}(1) \rightarrow \{-1, 1\}$  such that  $\varphi : \tilde{M}(1) \times \tilde{N}(1) \rightarrow \widetilde{M \times N}(1) \times \{-1, 1\}$  by  $\varphi(u, v) = (\mu| (u, v), q(u, v))$  is a homeomorphism. Hence the LHS is not connected, but if  $\tilde{M}(1)$  and  $\tilde{N}(1)$  are both non-orientable, then they are connected, and so is their product, so we obtain that at least one of them must be orientable.  $\square$

**Exercise 1.32.** Every manifold has a unique  $\mathbb{Z}/2$ -orientation.

*Proof.* The sections  $\Gamma(M; \mathbb{Z}/2)$  of  $\omega$  correspond bijectively to continuous maps  $\lambda : \text{Ori}(M) \rightarrow \mathbb{Z}/2$  such that  $\lambda \circ t = -\lambda$ . Hence we only have the 0 section and the constant section corresponding to the constant nontrivial map  $\text{Ori}(M) \rightarrow \mathbb{Z}/2$ . The latter is in particular an orientation.  $\square$

**Exercise 1.33.** If  $M$  is a connected manifold such that  $\pi_1(M)$  has no subgroups of index 2, then show that  $M$  is orientable.

*Proof.* If  $M$  is not orientable, then  $\text{Ori}(M)$  is a connected covering space. Manifolds are locally-path connected and semi-locally simply connected, so by the classification of covering spaces (using connectedness of  $M$ ),  $\text{Ori}(M)$  corresponds to a subgroup of index 2 of  $\pi_1(M)$  [1, Corollary 6.9].  $\square$

**Exercise 1.34.** Let  $p: M \rightarrow N$  be a covering map of  $n$ -manifolds. Then the pullback of  $\text{Ori}(N) \rightarrow N$  along  $p$  is  $\text{Ori}(M) \rightarrow M$ .

*Proof.* The pullback of a covering map is a covering map. We have the following diagram

$$\begin{array}{ccccc}
 \text{Ori}(M) & & & & \\
 \searrow q & \dashrightarrow & \text{Ori}(N) \times_N M & \xrightarrow{\quad} & \text{Ori}(N) \\
 & & \downarrow \tilde{\pi} & & \downarrow \pi \\
 & & M & \xrightarrow{\quad p \quad} & N
 \end{array}$$

Since  $q$  and  $\tilde{\pi}$  are local homeomorphisms and  $\tilde{\pi}^{-1} \circ q$  is bijective, we obtain that  $\tilde{\pi}^{-1} \circ q$  is a bundle isomorphism. Thus the pullback is the orientation bundle.  $\square$

**Exercise 1.35.** Show that the manifold  $\text{Ori}(M)$  is always orientable.

*Proof.* Recall that the orientation bundle of  $\text{Ori}(M)$  is

$$\omega_{\text{Ori}(M)}: H_n(\text{Ori}(M), \text{Ori}(M) - \bullet) \rightarrow \text{Ori}(M)$$

But  $\omega$  is a local homeomorphism, so

$$\begin{aligned}
 \omega_*: H_n(\text{Ori}(M), \text{Ori}(M) - u) &\cong H_n(\text{Ori}(M) - (\text{Ori}(M) - V_z), (\text{Ori}(M) - u) - (\text{Ori}(M) - V_z)) \\
 &\cong H_n(V_z, V_z - u) \\
 &\cong H_n(V, V - \omega u) \\
 &\cong H_n(M, M - \omega u) \ni u
 \end{aligned}$$

So at the point  $u \in \text{Ori}(M)$ , we can define  $s(u)$  to be the image of  $u$  under this line of isomorphisms.

Note that no  $\tilde{M}(n)$  is distinguished from  $\tilde{M}(1)$ . Indeed,  $\tilde{M}(n)$  is homeomorphic to  $\tilde{M}(1)$  under the isomorphism  $u \mapsto n \cdot u$  from  $\tilde{M}(1)$  to  $\tilde{M}(n)$  which commutes with  $\omega_*$  because  $\omega$  is a local homeomorphism.

$$\begin{array}{ccc}
 H_n(\tilde{M}(1), \tilde{M}(1) - u) & \xrightarrow{\omega_*} & H_n(M, M - \omega u) \\
 \downarrow \cdot n & & \downarrow \cdot n \\
 H_n(\tilde{M}(n), \tilde{M}(n) - nu) & \xrightarrow{\omega_*} & H_n(M, M - \omega nu)
 \end{array}$$

$\square$

## 2. DUALITY

Let  $M^n$  be orientable and  $\vartheta_M \in \Gamma(M, H_n(M, M - \bullet))$  an orientation.

For  $K \subset M$  compact,  $\vartheta_M$  restricts to  $\vartheta_K \in \Gamma(K, H_n(M, M - \bullet)) = \Gamma_c(K, H_n(M, M - \bullet)) \cong H_n(M, M - K)$ , so we can regard  $\vartheta_K$  as lying in  $H_n(M, M - K)$ . Let  $\vartheta = \{\vartheta_K\}$  be the collection of all these, and we then call  $\vartheta$  an orientation.

**Definition 2.1.** For sets  $L \subset K \subset M$ , we define

$$\check{H}^p(K, L; G) = \varinjlim \{H^p(U, V; G) \mid (U, V) \supset (K, L), U, V \text{ open}\}.$$

This is a directed system since if  $(U, V)$  and  $(U', V')$  both contain  $(K, L)$ , the  $(U \cap U', V \cap V')$  also contains  $(K, L)$ , and the maps induced by inclusions of nested open sets satisfy the required relation to be a directed system.

This group is naturally isomorphic to that of Čech cohomology. If  $K$  and  $L$  are spaces such as ENRs (e.g., CW-complexes or topological manifolds), then this is also naturally isomorphic to singular cohomology.

**2.1. Construction of the duality map.** Suppose  $(K, L) \subset (U, V)$  as above (so  $L \subset K$ ). Then note that since  $K \subset U$ , we have  $M - U = \overline{M - U} \subset \int(M - K) = M - K$ , so by excision,  $H_{n-p}(U - L, U - K) \cong H_{n-p}(M - L, M - K)$ . Also,  $\{V, U - L\}$  is an open cover of  $U$ , hence  $H_*\left(\frac{\Delta_*(V) + \Delta_*(U - L)}{\Delta_*(U - K)}\right) \cong H_*(U, U - K) \cong H_*(M, M - K)$  where the first isomorphism follows from Theorem 7.2.2 in Algtop1, and the latter follows from excision.

Now, we have a well-defined cap product

$$\Delta^p(U, V; G) \otimes \left[ \frac{\Delta_n(V) + \Delta_n(U - L)}{\Delta_n(U - K)} \right] \rightarrow \Delta_{n-p}(U - L, U - K; G)$$

given by  $f \cap (b + c) = f \cap b + f \cap c = f \cap c$ , which by the above, induces a cap product

$$H^p(U, V; G) \otimes H_n(M, M - K) \rightarrow H_{n-p}(M - L, M - K; G)$$

which is natural in  $(K, L)$ .

Using the same theorem from Algtop1, we find that for  $\gamma \in H_n(M, M - A)$ , we can represent  $\gamma$  by a chain  $b + c + d \in \Delta_n(V) + \Delta_n(U - L) + \Delta_n(M - K)$ , so for  $f \in \Delta^p(U, V; G)$ , we get that

$$[f] \cap \gamma = [f \cap (b + c + d)] = [f \cap c] \in H_{n-p}(M - L, M - K; G)$$

since  $f \cap b = 0$  as  $f$  vanishes on  $V$  and  $f \cap d$  is a chain in  $M - K$ .

Thus by capping with  $\vartheta_A$  for  $A$  large enough to contain  $K$ , we obtain a homomorphism

$$\cap \vartheta: H^p(U, V; G) \rightarrow H_{n-p}(M - L, M - K; G).$$

Now, recall that the direct limit used for  $\check{H}$  has the universal property that it is the colimit under the direct system. So if the above map  $\cap \vartheta$  is compatible with the direct system, then we will obtain an induced homomorphism from  $\check{H}$ .

Suppose  $i: (U', V') \hookrightarrow (U, V)$  is the inclusion. Let  $[f] \in H^p(U, V; G)$  and represent  $\vartheta$  as  $b + c + d \in \Delta_n(V') + \Delta_n(U' - L) + \Delta_n(M - A)$ . Then

$$[f] \cap \vartheta = [f \cap (b + c + d)] = [f \cap c] = [f \circ i \cap c] = i^* [f] \cap \vartheta$$

so the homomorphism is compatible with the morphisms in the directed system. Furthermore, choosing a different  $A$ , say  $A'$ , we similarly can write  $\vartheta$  as  $b + c + d \in \Delta_n(V') + \Delta_n(U' - L) + \Delta_n(M - A')$ , and again  $f \cap d$  becomes zero in homology since it lands inside  $M - A \subset M - K$ . Hence the homomorphism  $\cap \vartheta$  is compatible with changing  $A$  and also with the directed system maps. Thus in the direct limit, we get a natural map

$$\cap \vartheta: \check{H}^p(K, L; G) \rightarrow H_{n-p}(M - L, M - K; G).$$

**2.2. Properties of the duality map.** Now that we have constructed the homomorphism we are interested in, we should prove some properties that might be useful for us.

In order to do this, we give its (co)chain description.

Let  $\alpha \in \check{H}^p(K, L; G)$ . Then by the direct limit, there exists some open neighborhood  $(U, V)$  of  $(K, L)$  such that  $\alpha$  is represented by a  $p$ -cocycle  $f$  of  $(U, V)$ . Thus  $f = 0$  on  $V$  and  $\delta f = 0$  on  $U$ . Then extend  $f$  trivially to a cochain on all of  $M$ . We represent the orientation  $\vartheta$  by a chain  $a = b + c + d \in \Delta_n(V) + \Delta_n(U - L) + \Delta_n(M - K)$ . Then  $f \cap (b + c + d) = f \cap b + f \cap c + f \cap d$ . But  $f \cap b = 0$  and  $f \cap d$  is a chain in  $M - K$ , so  $\alpha \cap \vartheta$  is represented by  $f \cap c$ . In the special case for  $L = \emptyset$ , we take  $V = \emptyset$ , so  $b$  does not come into the consideration then.

Using the above description, we can now show the following lemma

**Lemma 2.2.** *The following diagram with arbitrary coefficients has exact rows and commutes:*

$$\begin{array}{ccccccc}
 \dots & \longrightarrow & \check{H}^p(K, L) & \longrightarrow & \check{H}^p(K) & \longrightarrow & \check{H}^p(L) \longrightarrow \check{H}^{p+1}(K, L) \longrightarrow \dots \\
 & & \downarrow & & \downarrow & & \downarrow \\
 \dots & \longrightarrow & H_{n-p}(M - L, M - K) & \longrightarrow & H_{n-p}(M, M - K) & \longrightarrow & H_{n-p}(M, M - L) \longrightarrow H_{n-p-1}(M - L, M - K) \longrightarrow \dots
 \end{array}$$

where all vertical maps are the cap products with the orientation class  $\vartheta$ .

*Proof.* The exactness of the top row follows from Theorem 1.16 together with the LES of a pair in singular cohomology.

Let us first check the first two squares. In the first one, if  $[f] \in \check{H}^p(K, L)$ , then going down, we get  $[f] \cap \vartheta$  which includes into  $H_{n-p}(M, M - K)$ . In particular, this is represented by  $f \cap c$ . But in the same way, including first  $[f]$  into  $\check{H}^p(K)$  and the capping with  $\vartheta$  is still represented by  $f \cap c$  (as we discussed above), so we obtain commutativity of the first square. For the second square, suppose let  $f \in \Delta^p(M; G)$  be such that  $f|_U \in \Delta^p(U; G)$  represents  $\alpha \in H^p(U; G)$  mapping to the class in question in  $\check{H}^p(K; G)$ . Let  $\vartheta$  be represented by  $a = b + c + d \in \Delta_n(V) + \Delta_n(U - L) + \Delta_n(M - K)$ . Then  $f \cap a$  is represented by  $f \cap b + f \cap c$  in  $H_{n-p}(M, M - K)$ . But since we have the decomposition  $a = 0 + b + (c + d) \in \Delta_n(\emptyset) + \Delta_n(V - \emptyset) + \Delta_n(M - L)$ , we also have that in  $H_n(M, M - L)$ ,  $f \cap a$  becomes  $f \cap b$ .

On the other hand, we have  $f$  restricting to class which is the image of a class represented by  $f|_V$ . But then this simply becomes  $f|_V \cap b = f \cap b$  in  $H_{n-p}(M, M - L)$ .

For the last square, we must check commutativity.

Let  $f \in \Delta^p(M; G)$  such that  $f|_V \in \Delta^p(V; G)$  represents  $\alpha \in H^p(V; G)$  mapping to the class in  $\check{H}^p(L; G)$  that we want to chase through the square (we can find such an  $f$  by the properties section above the lemma). Thus  $\delta f = 0$  on  $V$ .

Now represent  $\vartheta$  by  $a = b + c + d \in \Delta_n(V) + \Delta_n(U - L) + \Delta_n(M - K)$ . This is the decomposition of  $a$  appropriate to the  $(K, L)$  pair, but we can also decompose  $a$  as  $a = 0 + b + (c + d) \in \Delta_n(\emptyset) + \Delta_n(V - \emptyset) + \Delta_n(M - L)$  which is the decomposition with respect to the pair  $(L, \emptyset)$ , showing that  $a$  can be used in the definition of both the cap product for  $\check{H}^p(L)$  and for  $\check{H}^{p+1}(K, L)$  in question. Since  $\vartheta$  is a class of  $(M, M - K)$ ,  $\partial a$  is a chain in  $M - K$ . Now, starting with  $f$  representing  $\alpha$ , going to the right gives  $\delta f$  and then capping with  $a$  when going down gives  $\delta f \cap a$ . On the other hand, going down with  $f$  first gives  $f \cap a$  and going right then gives  $\partial(f \cap a)$ .



Now recall that  $\partial(f \cap a) = (\delta f) \cap a \pm f \cap \partial a$ , but  $f \cap \partial a$  is a chain in  $M - K$ , so it vanishes on passage to homology, whereby we find that the square commutes.  $\square$

**Lemma 2.3.** *Let  $K$  and  $L$  be compact subsets of the  $n$ -manifold  $M$  with the orientation  $\vartheta$ . Then the diagram with arbitrary coefficients*

$$\begin{array}{ccccccc} \dots & \longrightarrow & \check{H}^p(K \cup L) & \longrightarrow & \check{H}^p(K) \oplus \check{H}^p(L) & \longrightarrow & \check{H}^p(K \cap L) \xrightarrow{\delta^*} \check{H}^{p+1}(K \cup L) \longrightarrow \dots \\ & & \downarrow & & \downarrow & & \downarrow \\ \dots & \longrightarrow & H_{n-p}(M, M - (K \cup L)) & \longrightarrow & H_{n-p}(M, M - K) \oplus H_{n-p}(M, M - L) & \longrightarrow & H_{n-p}(M, M - (K \cap L)) \xrightarrow{\delta_*} H_{n-p-1}(M, M - (K \cup L)) \longrightarrow \dots \end{array}$$

*where the vertical maps are the cap products with  $\vartheta$ , commutes and has exact rows.*

### 3. INTERSECTION THEORY

#### 3.1. The Thom class of a disk bundle.

**Definition 3.1** ( $k$ -disk bundle). A  $k$ -disk bundle is a vector bundle whose coordinate transformations are contained in  $O(k) \subset \text{GL}(\mathbb{R}^k)$  and such that the local trivializations have the form  $\pi^{-1}(U) \cong U \times D^k$ .

Let  $N^n$  be a connected, oriented, closed  $n$ -manifold, and  $W^{n+k}$  an  $(n+k)$ -manifold with boundary  $\partial W$  a  $(k-1)$ -sphere bundle over  $N^n$ , and let  $\pi: W^{n+k} \rightarrow N^n$  be a  $k$ -disk bundle over  $N$ .

Let us assume that  $W$  is also oriented.

**Definition 3.2.** In the above situation, the *Thom class* of the disk bundle  $\pi$  is the class  $\tau \in H^k(W, \partial W)$  given by

$$\tau = D_W(i_*[N])$$

where  $D_W: H_{n-k}(W) \rightarrow H^k(W, \partial W)$  is the inverse of the Poincaré duality isomorphism. That is,

$$D(a) \cap [M] = a.$$

Thus

$$\tau \cap [W] = i_*[N].$$

We can deformation retract the punctured disk to its boundary, giving  $H^k(W, W - N) \cong H^k(W, \partial W)$ , so we will sometimes regard  $\tau$  as being in  $H^k(W, W - N)$ .

**3.2. Transfer maps.** *Transfer* maps, also called *shriek* or *umkehr* maps, are a particular class of maps that exhibit some nice properties.

We give a definition that suffices for our purposes, but this class of maps can be treated more generally (See e.g. [5]).

**Definition 3.3** (Transfer map). If  $f: N^n \rightarrow M^m$  is a map from a compact oriented  $n$ -manifold  $N$  to a compact, oriented  $m$ -manifold  $M$ , taking  $\partial N$  into  $\partial M$ , then

$$f^!: H^{n-p}(N) \rightarrow H^{m-p}(M) \quad \text{and} \quad f^!: H^{n-p}(N, \partial N) \rightarrow H^{m-p}(M, \partial M)$$

are defined by

$$f^! = D_M f_* D_N^{-1}.$$

Similarly,

$$f_!: H_{m-p}(M) \rightarrow H_{n-p}(N) \quad \text{and} \quad f_!: H_{m-p}(M, \partial M) \rightarrow H_{n-p}(N, \partial N),$$

are both defined by

$$f_! = D_N^{-1} f^* D_M.$$

Our particular interest will lie in the transfer map  $i_!$  when  $i$  is an embedding of a closed oriented manifold.

This transfer map and the Thom class of a  $k$ -disk bundle are intimately connected as described in the Thom isomorphism theorem, a version of which we now state.

**Theorem 3.4** (Thom Isomorphism Theorem, first version). *If  $\pi: W \rightarrow N$  is a  $k$ -disk bundle over a connected oriented closed  $n$ -manifold  $N^n$ , then there is the "Thom Isomorphism"*

$$H^p(N) \xrightarrow{\pi^*} H^p(W) \xrightarrow{\cup \tau} H^{p+k}(W, \partial W)$$

which coincides with  $i^!$ . Similarly,  $i_! = \pm \pi_* \circ (\tau \cap -) : H_{p+k}(W, \partial W) \rightarrow H_p(N)$  is an isomorphism.

*Proof.* Direct computation from the definition □

We can extend this isomorphism a bit to disk bundles over base spaces which are not necessarily manifolds, but which are embedded in manifolds.

**Lemma 3.5.** *In the above setup, suppose  $A \subset N$  is closed. Let  $\tilde{A} = \pi^{-1}(A) \subset W$  and  $\partial \tilde{A} = \tilde{A} \cap \partial W$ . Then  $\check{H}^i(\tilde{A}, \partial \tilde{A}) = 0$  for  $0 < i < k$ .*

*Proof.* Suppose first that  $A$  is compact convex subset of a Euclidean neighborhood in  $N$ . It also suffices consider the case where  $A$  is connected, so  $A \cong D^n$ . Consider the pullback bundle of  $A$ :

$$\begin{array}{ccc} i^*(A) & \longrightarrow & W \\ \downarrow & & \downarrow \pi \\ A & \xhookrightarrow{i} & N \end{array}$$

Then  $i^*(A) = A \times_N W \cong \pi^{-1}(A)$ , so since any vector bundle over a contractible paracompact base space is trivial, we conclude that the bundle  $\tilde{A} \rightarrow A$  is trivializable as  $\tilde{A} \cong A \times D^k$  and  $\partial \tilde{A} \cong A \times S^{k-1}$ . Now the steps are as follows: calculate the homology of  $A \times D^k$  and  $A \times S^{k-1}$ , then use UCT to obtain the cohomology, and then use the LES to find the cohomology of  $(A \times D^k, A \times S^{k-1})$ .

Now... But by the Künneth theorem,

$$H_m(A \times D^k) \cong H_m(A)$$

and

$$H_m(A \times S^{k-1}) \cong H_m(A) \oplus H_{m-k+1}(A).$$

□

**Lemma 3.6.** *The restriction  $\tau_x \in \check{H}^k(\tilde{A}, \partial \tilde{A})$  of  $\tau$ , when  $A = \{x\}$ , is a generator.*

*Proof.* Note that  $(\tilde{A}, \partial \tilde{A}) \cong (D^k, S^{k-1})$ .

Suppose first that  $\tau_x = 0$  for some  $x$ . Let  $i: \tilde{A} \hookrightarrow W$  be the inclusion, then we have

$$0 = i_*(0) = i_*(\tau_x \cap \beta) = \tau \cap i_*(\beta),$$

for all  $\beta \in H_*(\tilde{A}, \partial \tilde{A})$ .

Let  $U$  be a neighborhood around  $x$  which is evenly covered, so  $\pi^{-1}(U) \cong U \times D^k$ , and  $\tilde{A} = \pi^{-1}(x) \cong \{x\} \times D^k$ . Let  $i_x: \{x\} \rightarrow \{x\} \times D^k$  be the zero section, and

similarly for  $i_y: \{y\} \rightarrow \{y\} \times D^k$ . Let  $\gamma: I \rightarrow U$  be a path from  $x$  to  $y$ . Then we can define a path  $F: I \rightarrow U \times D^k$  by  $F(t) = (\gamma(t), 0)$ . Then  $F(t) = i_{\gamma(t)}(\gamma(t))$ . We have a pullback square as follows:

$$\begin{array}{ccc} (X, X') & \longrightarrow & (W, W') \\ \downarrow q & & \downarrow p \\ I & \longrightarrow & B \end{array}$$

Then we have an isomorphism induced by inclusions:

$$w_{\#}: H_n(F_c, F'_c) \xrightarrow{\cong} H_n(X, X') \xleftarrow{\cong} H_n(F_b, F'_b)$$

In particular,  $i_{c*} = i_{b*}w_{\#}$ , so if  $i_{c*}[x] = 0$ , then  $i_{b*}[y] = i_{b*}w_{\#}[x] = \pm i_{c*}[x] = 0$ . Thus  $\tau_y = 0$  for all  $y$  near  $x$ . Since  $N$  is connected, this implies that  $\tau_y = 0$  for all  $y \in N$ .

By  $\tau$  restricting to zero at every point does not necessarily imply a priori that  $\tau$  is zero. But we can use it for a Bootstrap argument.

For closed sets  $A \subset N$ , let  $P_N(A)$  be the statement that  $\tau_A = 0$ , where  $\tau_A = \tau|_{(\tilde{A}, \partial\tilde{A})}$ .

Suppose now that  $A$  is a convex set in some euclidean open set in  $N$ .

Note that

$$\check{H}^k(\tilde{A}, \partial\tilde{A}) \cong \check{H}^k(W - (W - \tilde{A}), (W - \tilde{A})) \cong \check{H}^k(W, W - \tilde{A})$$

so we can regard  $\tau|_A \in \check{H}^k(\tilde{A}, \partial\tilde{A})$  as living in  $\check{H}^k(W, \tilde{A})$ .

We have that the restriction defines an isomorphism

$$H^n(W, W - \tilde{A}) \rightarrow H^n(W, W - x)$$

if  $\tilde{A}$  is a compact convex set contained in a Euclidean neighborhood. Since  $\tilde{A}$  is locally of the form  $C \times D^k$  for  $C$  convex, we see that for every  $x \in \tilde{A}$ , there is a ball at  $x$  such that its intersection with  $\tilde{A}$  is convex. I.e.,  $\tilde{A}$  is locally convex. Also, it is closed, so each component is convex by the Tietze-Nakajima Theorem. Since the local structure of  $\tilde{A}$  is as  $U \times D^k$ , we can for any two points in  $\tilde{A}$  choose a path between the points in the image of  $\pi$  below, and run through this path in the zero section above and then run the rest in  $D^k$  to connect the points. Hence  $\tilde{A}$  is also connected, hence convex. Now Proposition 1.3 gives that  $\check{H}^k(W, W - \tilde{A}) \cong \check{H}^k(W, W - \tilde{x})$  for  $\tilde{x} \in \tilde{A}$ .

Also, we have an isomorphism

$$H_n(W, W - \tilde{A}) \cong H_n(N, N - A) \xrightarrow{\cong} H_n(N, N - x) \cong H_n(W, W - \pi^{-1}(x))$$

Let  $X = \pi^{-1}(x)$ , and  $\partial X = X \cap \partial W$ . Let  $U$  be a neighborhood of  $x$  such that  $\pi^{-1}(U) \cong U \times D^k$ .

$$\begin{aligned} \check{H}^k(W, W - X) &\cong \check{H}^k(W - (W - \pi^{-1}(U)), (W - X) - (W - \pi^{-1}(U))) \\ &\cong \check{H}^k(\pi^{-1}(U), \pi^{-1}(U) - X) \\ &\cong \check{H}^k(X, \partial X) \end{aligned}$$

Note that  $\tau_x = i^* \tau_A$  where  $i: \pi^{-1}(x) \hookrightarrow \tilde{A}$  is the inclusion, so if  $i^*: H^k(\tilde{A}, \partial \tilde{A}) \rightarrow H^k(\pi^{-1}(x), \pi^{-1}(x) \cap \partial W)$  is injective, then since  $\tau_x = 0$ , we obtain  $\tau_A = 0$ .

Now, because  $A$  is a convex set in some Euclidean space, we can shrink  $A$  to be small enough so that, when considered in  $N$ , we have  $\pi^{-1}(A) \cong A \times D^k$ , and this deformation retract onto  $\{x\} \times D^k$ , so indeed  $i$  must be a homotopy equivalence (in fact,  $\pi^{-1}(A) \cong A \times D^k$  directly since  $A$  is contractible and vector bundles over contractible spaces are trivial).

Next, if  $P_N(A)$  and  $P_N(B)$  hold, then  $P_N(A \cup B)$  follows from the diagram

$$\begin{array}{ccccc} \underbrace{H^{k-1}(W \cap W, \partial(W \cap W))}_{=0} & \longrightarrow & H^k(W \cup W, \partial(W \cup W)) & \longrightarrow & H^k(W, \partial W) \oplus H^k(W, \partial W) \\ & & \downarrow & & \downarrow \\ \underbrace{\check{H}^{k-1}(\tilde{A} \cap \tilde{B}, \partial(\tilde{A} \cup \tilde{B}))}_{=0} & \longrightarrow & \check{H}^k(\tilde{A} \cup \tilde{B}, \partial(\tilde{A} \cup \tilde{B})) & \longrightarrow & \check{H}^k(\tilde{A}, \partial \tilde{A}) \oplus \check{H}^k(\tilde{B}, \partial \tilde{B}) \end{array}$$

Here we used Theorem 1.16 to take  $\check{H}$  on the bottom row. In this case, the rightmost map is  $i_{(\tilde{A}, \partial \tilde{A})}^* \oplus i_{(\tilde{B}, \partial \tilde{B})}^*$ , which maps  $(\tau, \tau)$  to  $(\tau_A, \tau_B)$ , and the left map is the restriction  $i_{(\tilde{A} \cup \tilde{B}, \partial(\tilde{A} \cup \tilde{B}))}^*$ .

The top map is  $j^* \oplus -j^*$  where  $j$  is the inclusion of  $W$  into  $W$ . Hence the map along the top and right arrow takes  $\tau$  to  $(\tau_A, -\tau_B) = (0, 0)$ , and the map along the left takes  $\tau$  to  $\tau_{A \cup B}$  which is mapped to  $(0, 0)$  along the bottom injectively. Hence  $\tau_{A \cup B} = 0$ .

Next suppose  $P_N(A_i)$  holds for each set of decreasing sequences of closed sets  $A_1 \supset A_2 \supset \dots$ . Then  $\check{H}^k(A) = \lim_{\rightarrow} \check{H}^k(A_i) = 0$  since Čech cohomology commutes with direct limits. By assumption,  $N$  is closed, so by the Bootstrap lemma,  $P_N(N)$  holds. That is,  $\tau = 0$ , however, this is impossible, since  $\tau$  is the image of  $[N]$  under isomorphisms, and  $[N]$  is nontrivial by assumption.

We thus can conclude that  $\tau_x \neq 0$  for all  $x$ .

Suppose next that  $\tau_x$  is simply not a generator for some  $x$ , so say  $\tau_x \in H^k(D^k, S^{k-1}) \cong \mathbb{Z}$  corresponds to  $\pm m$ . Let  $p$  be a prime dividing  $m$ . Then in passing to  $\mathbb{Z}_p$  coefficients,  $\tau_x$  becomes trivial, but all of the above goes through the same in this setting, hence we conclude that  $\tau_x$  must correspond to  $\pm 1$ , i.e., a generator.  $\square$

**Corollary 3.7.** *If  $N$  is connected, then the Thom class  $\tau \in H^k(W, \partial W)$  is (up to sign) the unique class whose restriction to the fiber over each point is a generator.*

*Proof.* The Thom isomorphism gives  $\mathbb{Z} \cong H^0(N) \cong H^0(W) \rightarrow H^k(W, \partial W)$ , so if some class  $\alpha \in H^k(W, \partial W)$  restricts under  $\mathbb{Z} \cong H^k(W, \partial W) \rightarrow H^k(\pi^{-1}(x), \pi^{-1}(x) \cap \partial W) \cong H^k(D^k, S^{k-1}) \cong \mathbb{Z}$  to a generator, then it must be a generator in  $H^k(W, \partial W)$  also. By Lemma 3.6 above,  $\tau$  does restrict to a generator of each fiber, so  $\alpha$  equals  $\tau$  up to sign.  $\square$

**Theorem 3.8** (Thom Isomorphism Theorem, second version). *In the above situation, for any compact  $A \subset N$ , the map*

$$\pi(-) \cup \tau_A: \check{H}^i(A) \rightarrow \check{H}^{i+k}(\tilde{A}, \partial \tilde{A})$$

is an isomorphism.

*Proof.*

□

Bootstrap lemma

### 3.3. The Thom class arising from the normal bundle of submanifolds.

Suppose now that  $i_N^W: N^n \rightarrow W^w$  is a smooth embedding of a smooth manifold, possibly with boundary, and assume that  $N$  meets  $\partial W$  transversally in  $\partial N$ .

**Definition 3.9.** In the above situation, denote  $i_{N*}^W [N] \in H_n(W, \partial W)$  by  $[N]_W$ , and define  $\tau_N^W = D_W([N]_W) \in H^{w-n}(W)$ , which we will also call the Thom class of  $N$  in  $W$ . Here  $D_W: H_n(W, \partial W) \xrightarrow{\cong} H^{w-n}(W)$ .

We will show that the Thom class  $\tau_N^W$  is the *image* of the Thom class of the normal  $(w-n)$ -disk bundle  $\nu_N^W$  of  $N$  in  $W$  via

$$\varphi: H^{w-n}(\Xi, \Xi - N) \cong H^{w-n}(W, W - N) \rightarrow H^{w-n}(W)$$

where the first map is the inverse of the excision isomorphism.

Let  $u_N = D((i_N^\Xi)_* [N]) \in H^{n-w}(\Xi, \Xi - N)$  denote the Thom class of the normal disk bundle. Let  $u_N^{W, W-N}$  denote the inverse of  $u_N$  under the excision isomorphism, and let  $u_N^W$  denote the image of  $u_N^{W, W-N}$  under the restriction homomorphism. Then

**Lemma 3.10.**  $\tau_N^W = u_N^W \in H^{w-n}(W)$ .

*Proof.* By Poincaré duality, it suffices to show that

$$[N]_W = u_N^W \cap [W] \in H_n(W)$$

Consider the commutative diagram

$$\begin{array}{ccccc} H_n(\Xi) & \xrightarrow{i_{\Xi*}^W} & H_n(W) & \xleftarrow{\cap} & H^{w-n}(W) \otimes H_n(W) \\ \cap \uparrow & & \cap \uparrow & & \uparrow \\ H^{w-n}(\Xi, \Xi - N) \otimes H_w(\Xi, \Xi - N) & \xleftarrow{\quad} & H^{w-n}(W, W - N) \otimes H_w(W, W - N) & \xleftarrow{\quad} & H^{w-n}(W, W - N) \otimes H_n(W) \end{array}$$

The middle map takes  $u_N^{W, W-N} \otimes [W]$  to  $u_N^{W, W-N} \cap [W]$ , and going around the left square instead, it takes  $u_N^{W, W-N} \otimes [W] \mapsto u_n \otimes [\Xi] \mapsto u_n \cap [\Xi] = (i_N^\Xi)_* [N] \mapsto (i_\Xi^W)_* (i_N^\Xi)_* [N] = (i_N^W)_* [N] = [N]_W$

As for the right square, if we start with  $u_N^{W, W-N} \otimes [W]$  in the lower right, then this maps to  $[N]_W$  by construction along the bottom right map and middle map as we just saw, while going the other way around gives  $u_N^{W, W-N} \otimes [W] \mapsto u_N^W \otimes [W] \mapsto u_N^W \cap [W]$ , so by commutativity,  $u_N^W \cap [W] = [N]_W$ , from which the result follows. □

**3.4. The Intersection Product.** First, suppose  $M^n$  is a compact, oriented and connected manifold, possibly with boundary. Let  $D: H_i(M, \partial M) \rightarrow H^{n-i}(M)$  or  $D: H_i(M) \rightarrow H^{n-i}(M, \partial M)$  be the inverse of the Poincaré duality isomorphism, so

$$D(a) \cap [M] = a.$$

**Definition 3.11** (Intersection Product). We define the intersection product the composite

$$\bullet: H_p(M) \otimes H_q(M) \xrightarrow{D \otimes D} H^{n-p}(M) \otimes H^{n-q}(M) \xrightarrow{\times} H^{2n-p-q}(M^2) \xrightarrow{\Delta^*} H^{2n-p-q}(M) \xrightarrow{D^{-1}} H_{p+q-n}(M)$$

or  $H_p(M, \partial M) \otimes H_j(M) \rightarrow H_{i+j-n}$  or  $H_i(M, \partial M) \otimes H_j(M, \partial M) \rightarrow H_{i+j-n}(M, \partial M)$ .

Thus the intersection product of  $a$  and  $b$  is

$$a \bullet b = D^{-1}(D(b) \cup D(a)) = (D(b) \cup D(a)) \cap [M] = D(b) \cap (D(a) \cap [M]) = D(b) \cap a.$$

**Exercise 3.12.** Show that for homology classes  $a, b$  of  $M^n$ ,  $a \bullet b = (-1)^{n-\deg a} \Delta_!(b \times a)$ , where  $\Delta: M \rightarrow M \times M$  is the diagonal map.

*Proof.* By definition,

$$\begin{aligned} \Delta_!(b \times a) &= D^{-1} \Delta^* D_{(N, \partial N)}(b \times a) \\ &= \Delta^*(z) \cap [M] \end{aligned}$$

where  $z$  is the dual of  $b \times a$ , given by  $z \cap ([M] \times [M]) = b \times a$ . Let then  $x, y$  be the duals of  $b$  and  $a$ , respectively, so  $x \cap [M] = b$  and  $y \cap [M] = a$ . Note that  $\deg x = n - \deg b$ ,  $\deg y = n - \deg a$ . Then  $b \times a = (x \cap [M]) \times (y \cap [M]) = (-1)^{n-\deg a} (x \times y) \cap ([M] \times [M])$ . Hence  $z = (-1)^{n-\deg a} x \times y$ , so since  $\Delta^*(x \times y) = x \cup y$  by definition, we obtain

$$\begin{aligned} (-1)^{n-\deg a} \Delta_!(b \times a) &= \Delta^*(x \times y) \cap [M] \\ &= (x \cup y) \cap [M] \\ &= x \cap [y \cap [M]] \\ &= D(b) \cap a \\ &= a \bullet b. \end{aligned}$$

□

This lets us define the intersection product as follows instead:

**Definition 3.13.** Let  $M$  be an oriented manifold, and  $\Delta: M \rightarrow M \times M$  be the diagonal embedding. For arbitrary open pairs  $(V, S), (W, T)$  in  $M$ , consider the maps

$$\begin{aligned} H_i(V, S) \otimes H_j(W, T) &\xrightarrow{\sim} H_{i+j}(V \times W, S \times W \cup V \times T) \\ &\rightarrow H_{i+j}(V \times W \cup (M \times M - \Delta(M)), S \times W \cup V \times T \cup (M \times M - \Delta(M))) \\ &\xrightarrow{\Delta} H_{i+j-n}(V \cap W, (S \cap W) \cup (V \cap T)) \end{aligned}$$

The composite is the intersection product.

**3.5. The Intersection Product as a Thom-Pontrjagin Construction.** Let  $M$  be a manifold. We claim that  $TM \cong N\Delta$ , where  $N\Delta$  is the normal bundle of the diagonal as embedded in  $M \times M$ .

To see this, note first that  $T(M \times M) \cong TM \oplus TM$ . The tangent bundle of  $\Delta$  now sits inside this as the diagonal:  $TM \cong T\Delta \hookrightarrow TM \oplus TM$  induced by the diagonal map. Now,  $N\Delta = (TM \oplus TM)/T\Delta$  by definition, and for each point  $(p, v) \in TM$ , note that  $((p, v) \oplus TM) \cap T\Delta = ((p, v), (p, v))$ , meaning that each class in  $N\Delta$  has a unique representative with second coordinate being 0, hence  $(TM \oplus TM)/T\Delta \cong TM$ .

Next, identify  $TM$  with  $TM_\varepsilon$ , the subbundle of small vectors, i.e., length at most

$\varepsilon \ll \rho$  for  $\rho$  the injectivity radius of  $M$  [cf. Section 6]. With this identification, the map

$$\nu_M: TM \hookrightarrow M \times M, \quad \nu_M(x, v) = (x, \exp_x(v))$$

is a tubular neighborhood of  $\Delta$  whose image is the  $\varepsilon$  neighborhood of the diagonal

$$\text{im } \nu_M = U_M = \{(x, y) \in M \times M \mid |x - y| < \varepsilon\}.$$

Here the notion of distance makes sense because we assume  $M$  is a Riemannian manifold, and under this identification of  $TM$ , the bundle projection becomes the retraction  $r: U_M \rightarrow M$  by  $r(x, y) = x$ .

From  $\nu_M: TM \hookrightarrow M \times M$ , we obtain a map

$$\nu_M^*: \Delta^n(M \times M, M \times M - \Delta(M)) \xrightarrow{\sim} \Delta^n(TM, TM - M)$$

which is a quasi-isomorphism [cf. Section 6] as it induces an excision isomorphism. In  $C^n(TM, TM - M)$ , we have a representative of the Thom class for the tangent disk bundle, and we let  $\tau_M$  denote the image of this representative under  $(\nu_M^*)^{-1}$ , i.e.,  $\tau_M = (\nu_M^*)^{-1}(D(i_{M*}^{TM} m))$  where  $m$  is a representative for  $[M]$ .

We want to show a couple of things for  $\tau_M$ . First, we want  $\tau_M$  to have the property that

$$\tau_M \cap [M \times M] = \Delta_*[M] \in H_n(M \times M).$$

We can choose  $v_{M*}$  to map  $[TM]$  to  $[M \times M] \cong [M] \times [M]$ , in which case, certainly,

$$v_M^*(\tau_M) \cap [TM] = i_{M*}^{TM}[M],$$

so applying  $v_{M*}$ , we get

$$\tau_M \cap [M \times M] = \tau_M \cap v_{M*}[TM] = v_{M*}i_{M*}^{TM}[M] = \Delta_*[M].$$

Secondly, we claim that the following map of chain complexes induces the intersection product on  $H_*(M)$  up to the sign  $(-1)^{n(n-q)}$ :

$$\bullet_{Th}: \Delta_p(M) \otimes \Delta_q(M) \xrightarrow{\times} \Delta_{p+q}(M \times M) \xrightarrow{[\tau_M \cap]} \Delta_{p+q-n}(U_M) \xrightarrow{r_*} \Delta_{p+q-n}(M)$$

where the middle map is the following composition:

$$[\tau_M \cap]: \Delta_*(M \times M) \rightarrow \Delta_*(M \times M, M \times M - \Delta(M)) \xrightarrow{\sim} \Delta_*(U_M, U_M - \Delta(M)) \xrightarrow{\tau_M \cap} \Delta_{*-n}(U_M)$$

with the middle map being a chain homotopy inverse to excision.

To see this, consider the following diagram

$$\begin{array}{ccccccc} \Delta_p(M) \otimes \Delta_q(M) & \xrightarrow{\times} & \Delta_{p+q}(M \times M) & \xrightarrow{[\tau_M \cap]} & \Delta_{p+q-n}(U_M) & \xleftarrow{\Delta_*} & \Delta_{p+q-n}(M) \\ \uparrow \cap m \otimes \cap m & & \uparrow \cap m \times m & & & & \uparrow \cap m \\ \Delta^{n-p}(M) \otimes \Delta^{n-q}(M) & \xrightarrow{\times} & \Delta^{2n-p-q}(M \times M) & \xrightarrow{\Delta^*} & \Delta^{2n-p-q}(M) & & \end{array}$$

where  $m$  represents  $[M]$ .

The vertical maps have quasi-inverses as the chain complexes are lower bounded, so we can talk about the top composition, which is  $\bullet_{Th}$  compared to the other composition which induces  $\bullet$ .

The left hand square commutes up to chain homotopy and sign  $(-1)^{n(n-q)}$ , and the right square commutes directly. Also,  $r_*\Delta_* = (r\Delta)_* = \text{id}_*$ , so the two compositions commute up to chain homotopy, hence induce the same product on homology.

Check

Thus

$$a \bullet b = (-1)^{n(\deg a)} \Delta_!(b \times a) = (-1)^{n(\deg a)} a \bullet_{Th} b$$

In particular, this tells us that we can think of  $[\tau_M \cap]$  as counting the intersections with the zero section (at least in the case  $p+q = n$  and restriction to a neighborhood of the diagonal otherwise).



**3.6. Intersection Product Geometrically.** Below, manifolds will be assumed to be smooth, compact and oriented, and possibly with boundary.

Let  $i_N^W: N^n \rightarrow W^w$  be a smooth embedding of smooth manifolds with boundary, and assume that  $N$  meets  $\partial W$  transversally in  $\partial N$ .

**Definition 3.14** (Thom class). In the above situation, denote  $i_{N*}^W [N] \in H_n(W, \partial W)$  by  $[N]_W$ . Also define  $\tau_N^W = D_W([N]_W) \in H^{w-n}(W)$ , the *Thom class*. Here  $D_W: H_n(W, \partial W) \xrightarrow{\cong} H^{w-n}(W)$ . Thus

$$\tau_N^W \cap [W] = [N]_W$$

Suppose that  $K^k$  and  $N^n$  are two such submanifolds of  $W^w$ . Then

$$[K]_W \bullet [N]_W = (\tau_K^W \cap [W]) \bullet (\tau_N^W \cap [W]) = (\tau_N^W \cup \tau_K^W) \cap [W].$$

Assume now that  $K \pitchfork N$  in  $W$ . Then  $\nu_{K \cap N}^W = \nu_K^W|_{K \cap N}$  as a canonical isomorphism of vector bundles. (cf. [5, VIII, §11] for a homological interpretation as well).

This implies that the Thom class of  $K$  in  $W$  restricts to the Thom class of  $K \cap N$  in  $N$ , since its restriction to any point gives the generator in the cohomology of the fiber modulo its boundary, and the Thom class is characterized by this.

Hence  $\tau_{K \cap N}^W = (i_N^W)^*(\tau_K^W)$ .

**Theorem 3.15.** *With the assumptions above, including  $K \pitchfork N$  in  $W$ , we have*

$$\tau_{K \cap N}^W = \tau_K^W \cup \tau_N^W$$

and, equivalently,

$$[K \cap N]_W = [N]_W \bullet [K]_W.$$

*Proof.*

$$\begin{aligned} [K \cap N]_W &= i_{(K \cap N)*}^W [K \cap N] \\ &= i_{N*}^W i_{(K \cap N)*}^N [K \cap N] \\ &= i_{N*}^W (\tau_{K \cap N}^N \cap [N]) \\ &= i_{N*}^W (i_N^{W*} (\tau_N^W) \cap [N]) \\ &= \tau_K^W \cap i_{N*}^W [N] \\ &= \tau_K^W \cap (\tau_N^W \cap [W]) \\ &= (\tau_K^W \cup \tau_N^W) \cap [W] \\ &= [N]_W \bullet [K]_W \end{aligned}$$

□

**Corollary 3.16.** *Note that from proof, we obtain the following line:*

$$[K \cap N]_W = \tau_K^W \cap i_{N*}^W [N] = \tau_K^W \cap [N]_W$$

We interpret this result as saying that for transverse intersections, capping with the Thom class gives the fundamental class of the intersection in  $W$ .

**Theorem 3.17.** [1, VI, Theorem 11.10] Let  $M^n$  be an orientable closed manifold, and let  $A, B \subset M$ . Let  $\alpha \in H_p(A)$  and  $\beta \in H_q(B)$  and let  $\alpha_M$  and  $\beta_M$  denote their images in  $H_*(M)$ . If  $\alpha_M \bullet \beta_M \neq 0$ , then  $A \cap B \neq \emptyset$ .

**Example 3.18.** Take the transverse submanifolds  $K = S^n \times \{y_0\}$  and  $N = \{x_0\} \times S^m$  in  $S^n \times S^m$ . Then the fundamental classes of  $[K]$  and  $[N]$  in  $W = S^n \times S^m$  generate  $H_n(W)$  and  $H_m(W)$ , and the cup product of their duals generate  $H^{n+m}(S^n \times S^m)$ . This can be seen since  $K \cap N = (x_0, y_0)$ , so

$$[N]_W \bullet [K]_W = [K \cap N]_W = \pm [(x_0, y_0)]_W$$

which generates  $H_0(S^n \times S^m)$ . Hence  $\tau_K^W \cup \tau_N^W$  is a generator of  $H^{n+m}(S^n \times S^m)$ . Likewise, if  $K'$  is a shifted copy of  $K$ , then  $[K] \bullet [K] = [K] \bullet [K'] = [\emptyset] = 0$ , so  $(\tau_K^W)^2 = 0$ .

**Example 3.19.** Consider  $W = \mathbb{CP}^2$  and consider the copies of  $\mathbb{CP}^1$  by  $N = \{[z_0 : z_1 : 0]\}$  and  $K = \{[0 : z_1 : z_2]\}$ . Their intersection is a single point, so since they have transverse intersection,  $[N]$  and  $[K]$  are generators of  $H_2(\mathbb{CP}^2)$ , so  $[N] = \pm [K]$ . Thus  $(\tau_N^W)^2 = \tau_N^W \cup \tau_K^W = \tau_{N \cap K}^W$  is a generator of  $H^4(\mathbb{CP}^2)$ .

**Example 3.20.** Let  $N$  and  $K$  be submanifolds of  $W$  and suppose they have an odd number of transverse intersection points. Then  $[K] \in H_*(W; \mathbb{Z}/2)$  is nonzero since  $[K] \bullet [N] = [K \cap N] = \left[ \sum_{i=0}^{2k+1} x_i \right] =$

#### 4. GEOMETRIC HOMOLOGY THEORY

We have seen that the intersection product of two homology classes admits a nice geometric description when the homology classes can be represented by "nice enough" chains.

It is not obvious that this should be possible for other operations. Certain homology theories like bordism homology (See e.g. [4]) seem like promising theories to look at, but this is not in general equivalent to singular homology classes. However, M. Jakob showed that if we add some extra cohomological information, then we obtain a certain geometric homology theory that is equivalent to singular homology and makes it possible to approach many operations in a fairly geometric way. Let us start with constructing this homology theory.

**4.0.1. Geometric cycles.** Let  $X$  be a topological space. Then a geometric cycle is a triple  $(M, a, f)$  with  $f: M \rightarrow X$  a continuous map,  $M$  a smooth, compact, connected and oriented manifold without boundary, and  $a \in H^*(M; \mathbb{Z})$ .

If  $M$  is  $n$ -dimensional and  $a \in H^m(M; \mathbb{Z})$ , then  $(M, a, f)$  is assigned degree  $n - m$ . Let  $\Delta'_k(X)$  be the free abelian group generated by all geometric cycles of degree  $k$ . We impose the following relation:

$$(M, \lambda a + \mu b, f) = \lambda (M, a, f) + \mu (M, b, f).$$

**4.0.2. Relations.**

- (1) *Bordism relation.* Given a map  $h: W \rightarrow X$  where  $W$  is an oriented bordism between  $f(M)$  and  $g(N)$ , let  $i_1: M \hookrightarrow X$  and  $i_2: N \hookrightarrow X$  be the canonical inclusions. Then for any  $c \in H^*(W; \mathbb{Z})$ , we impose

$$(M, i_1^*(c), f) = (N, i_2^*(c), g).$$

This essentially says that we consider cycles in  $X$  to be geometrically homologous if they are connected by a bordism.

- (2) *Vector bundle modification.* Let  $(M, a, f)$  be a geometric cycle and consider a smooth oriented vector bundle  $E \xrightarrow{\pi} M$  equipped with a Riemannian metric. Then we can take the unit sphere bundle  $S(E \oplus 1) = \{v \in E \oplus 1 \mid \|v\| = 1\}$  of the Whitney sum of  $E$  with the trivial bundle over  $M$ . Consider the zero section  $\sigma_0: M \rightarrow E$  and any arbitrary nowhere zero section  $\sigma_1: M \rightarrow \mathbb{R}^k$ , for example  $\sigma_1(m) = (1, 0, \dots, 0)$ . Then  $\sigma' = \sigma_0 \oplus \sigma_1$  is a nonzero section, hence  $\sigma := \frac{\sigma'}{\|\sigma'\|}: M \rightarrow S(E \oplus 1)$  is a section. Let  $\sigma^!$  be the transfer associated to this section. We then impose

$$(M, a, f) = (S(E \oplus 1), \sigma^!(a), f\pi).$$

We denote the equivalence class of the geometric cycle  $(M, a, f)$  by  $[M, a, f]$ , and  $H'_q(X)$  the abelian group of geometric classes of degree  $q$ .

**Theorem 4.1.** [7, Corollary 2.3.6] *The morphism*

$$\begin{aligned} \text{compar}: H'_q(X) &\rightarrow H_q(X; \mathbb{Z}) \\ [M, a, f] &\mapsto f_*(a \cap [M]) \end{aligned}$$

*is a group isomorphism.*

**Theorem 4.2** (Cap Product and Poincaré duality). [3, §3.2, cites M. Jakob] The cap product between  $H^*(X; \mathbb{Z})$  and  $H'_*(X)$  is given by the following formula:

$$\begin{aligned} \cap: H^p(X; \mathbb{Z}) \otimes H'_q(X) &\rightarrow H'_{q-p}(X) \\ u \cap [M, a, f] &= [M, f^*(u) \cup a, f]. \end{aligned}$$

Let  $M$  be a  $n$ -dimensional smooth, compact, orientable manifold without boundary. Then the morphism

$$\begin{aligned} H^p(M; \mathbb{Z}) &\rightarrow H'_{n-p}(M) \\ x &\mapsto [M, x, \text{id}_M] \end{aligned}$$

is an isomorphism.

4.0.3. *Transfer maps.* We want to carry over transfer maps to geometric homology. Recall that for a map  $f: N^n \rightarrow M^m$ , we defined  $f_!: H_{m-p}(M) \rightarrow H_{n-p}(N)$  as the composite  $f_! = D_N^{-1} f^* D_M$ .

In the framework of geometric homology, we can give a very geometric interpretation of transfer maps.

Following [3, §3.3], start with  $i: X \rightarrow Y$  an oriented morphism of Hilbert manifolds and suppose that the virtual bundle  $V(i) = \ker di - \text{coker } di$  has rank  $-d$ . Define

$$i_!: H'_p(Y) \rightarrow H'_{p-d}(X)$$

as follows: let  $[M, a, f] \in H'_p(Y)$  and choose a representing cycle  $(M, a, f)$ . If  $f$  is not smooth, we can smoothly homotope it to a smooth one [3, §2.1.6] and moreover, we can choose it to be transverse to  $i$  [3, Theorem 2.2.4]. So suppose  $F: M \times I \rightarrow Y$  is this homotopy between  $f$  and  $f'$ . There are retractions  $r_L: M \times I \rightarrow M_L$  and  $r_R: M \times I \rightarrow M_R$ , where  $M_L, M_R$  are the left and right boundaries, respectively. It is clear that  $\tilde{a} = (r_L)^*(a) = (r_R)^*(a)$ , hence  $a = i_j^*(\tilde{a})$  for  $j = 1, 2$ , so by the bordism relation,  $[M, a, f] = [M, a, f']$ .

Then we can form the pullback:

$$\begin{array}{ccc} M \times_Y X & \xrightarrow{f^*i} & M \\ \downarrow \varphi & & \downarrow f \\ X & \xrightarrow{i} & Y \end{array}$$

**Theorem 4.3.** [3, Theorem 3.3.1] Let  $i: X \rightarrow Y$  be an oriented morphism of Hilbert manifolds of codimension  $d$ , and  $[M, a, f]$  a geometric cycle of  $H'_{p-a}(Y)$  such that  $f$  and  $i$  are transverse. Then set

$$i_!([M, a, f]) = (-1)^{d|a|} [M \times_Y X, (f^*i)^*(a), \varphi].$$

This gives a well-defined morphism

$$i_!: H'_*(Y) \rightarrow H'_{*-d}(X)$$

which satisfies

- (1) If we have a pullback of Hilbert manifolds  $X, Y$ :

$$\begin{array}{ccc} X' & \xrightarrow{j} & Y' \\ \downarrow \psi & & \downarrow \varphi \\ X & \xrightarrow{i} & Y \end{array}$$

- then  $i_! \varphi_* = \psi_* j_!$ ,
- (2) Let  $i$  and  $j$  be two composable oriented morphisms of Hilbert manifolds. Then  $i_! j_! = (ji)_!$
- (3) Let  $i_!^{PT}$  be the composition of the Pontryagin-Thom collapse  $\kappa$  and the Thom isomorphism  $th$ , then the following diagram commutes:

$$\begin{array}{ccc} H'_*(Y) & \xrightarrow{i_!} & H'_{*-d}(X) \\ \text{compar} \downarrow & & \downarrow \text{compar} \\ H_*(Y; \mathbb{Z}) & \xrightarrow{i_!^{PT}} & H_{*-d}(X; \mathbb{Z}) \end{array}$$

4.0.4. *The intersection product.* Likewise, we can redefine the intersection product. First, the cross product in geometric homology is given by

$$\begin{aligned} \times: H'_p(X) \otimes H'_q(Y) &\rightarrow H'_{p+q}(X \times Y) \\ [P, a, f] \times [Q, b, g] &= (-1)^{\dim(P)|b|} [P \times Q, a \times b, f \times g], \end{aligned}$$

such that if  $\tau: X \times Y \rightarrow Y \times X$  is the map interchanging the coordinates, then we have

$$\tau_*(\alpha \times \beta) = (-1)^{|\alpha||\beta|} \beta \times \alpha.$$

Suppose now that  $M$  is an oriented, compact,  $d$ -dimensional manifold. Let  $[P, x, f] \in H'_{n_1}(M)$  and  $[Q, y, g] \in H'_{n_2}(M)$ , and suppose  $f \pitchfork g$ . Then we form the pullback

$$\begin{array}{ccc} P \times_M Q & \xhookrightarrow{j} & P \times Q \\ \downarrow \varphi & & \downarrow f \times g \\ M & \xrightarrow{\Delta} & M \times M \end{array}$$

and define

$$\bullet: H'_{n_1}(M) \otimes H'_{n_2}(M) \xrightarrow{\times} H'_{n_1+n_2}(M \times M) \xrightarrow{\Delta^!} H'_{n_1+n_2-d}(M).$$

Hence,

$$[P, a, f] \bullet [Q, b, g] = (-1)^{d(|a|+|b|)+\dim(P)|b|} [P \times_M Q, j^*(a \times b), \varphi].$$

For  $l: P \times_M Q \rightarrow P$  and  $r: P \times_M Q \rightarrow Q$  the canonical inclusions, we have

$$[P, a, f] \bullet [Q, b, g] = (-1)^{d(|a|+|b|)+\dim(P)|b|} [P \times_M Q, l^*(a) \cup r^*(b), \varphi].$$

This makes  $H'_{*+d}(M)$  into a graded commutative algebra.

Note in particular that these definitions work on a chain level, so this definition of the intersection product gives a very geometric intuition as to what the intersection product does. In the transversal case, we take the intersection of the chains. Cf. [3] for further details.

## 5. STRING TOPOLOGY

**5.1. Product and Coproduct.** Let  $LM$  denote the free loop space of  $M$ , i.e.,

$$LM = \text{Map}(S^1, M).$$

Let  $\text{ev}_0: LM \rightarrow M$  denote the evaluation at 0.

We now introduce a product on the homology of the loop space of  $M$ , called the Chas-Sullivan product:

**5.1.1. One approach.** Consider the graded geometric homology group  $\mathbb{H}_*(LM) := H'_{*+d}(LM; \mathbb{Z})$ .

This group has some interesting structural properties, and string topology studies these underlying structures.

**5.1.2. The string pullback.** The evaluation map  $\text{ev}_0: LM \rightarrow M$  is, in fact, a smooth fiber bundle. To show this, one needs to first specify what the manifold structure of  $LM$  is. We will skip this part, but it is discussed in [3, §2.3.2].

Because  $\text{ev}_0$  is a smooth fiber bundle, it can locally be represented as a submersion, hence is transverse to any other map, so  $\text{ev}_0 \times \text{ev}_0$  is transverse to the diagonal map, and we can form the pullback

$$\begin{array}{ccc} LM \times_M LM & \xrightarrow{\tilde{\Delta}} & LM \times LM \\ \downarrow \text{ev}_0 & & \downarrow \text{ev}_0 \times \text{ev}_0 \\ M & \xrightarrow{\Delta} & M \times M \end{array}$$

By transversality, the pullback is again a Hilbert manifold. Also  $LM \times_M LM \cong \text{Map}(S^1, M)$ , and  $\tilde{\Delta}$  is a codimension  $d$  embedding. As the normal bundle  $\nu_{\tilde{\Delta}}$  is the pullback of  $\nu_{\Delta}$  (cf. Lemma 7.2), and since this last one is isomorphic to  $TM$ . But then  $\nu_{\Delta}$  admits a structure group reduction to  $\text{GL}_n^+(\mathbb{R})$  of its frame bundle, and so pulling back along  $f^*$  the coordinate charts gives a structure group reduction of the frame bundle for  $\nu_{\tilde{\Delta}}$ . We deduce that  $\tilde{\Delta}$  is an oriented morphism.

**Definition 5.1.** A family of closed string in  $M$  is a smooth map

$$f: P \rightarrow LM$$

from a compact oriented manifold  $P$ .

**Proposition 5.2.** [3, Prop 2.3.7] *The family  $P \times Q \xrightarrow{f \times g} LM \times LM$  is transverse to  $\tilde{\Delta}$  if and only if  $\text{ev}_0 f$  and  $\text{ev}_0 g$  are transverse in  $M$ .*

Now let  $(P, f)$  and  $(Q, g)$  be two families of dimensions  $p$  and  $q$ , respectively, such that  $f \times g$  is transverse to  $\tilde{\Delta}$ . Denote by  $P * Q$  the pullback

$$\begin{array}{ccc} P * Q & \longrightarrow & P \times Q \\ \downarrow \psi & & \downarrow f \times g \\ LM \times_M LM & \xrightarrow{\tilde{\Delta}} & LM \times LM \end{array} \quad (\Omega)$$

So we think of  $P * Q$  as the points in  $P \times Q$  that map under  $f \times g$  to loops with a common basepoint. The map  $\psi$  is the map taking a point in  $P * Q$  to this tuple of loops.

5.1.3. *Intersection of families of closed strings.* Define a map

$$\star: LM \times_M LM \rightarrow LM$$

by concatenating loops. That is

$$\star(\alpha, \beta) = \alpha \star \beta(t) = \begin{cases} \alpha(2t), & t \in [0, \frac{1}{2}] \\ \beta(2t - 1), & t \in [\frac{1}{2}, 1] \end{cases}$$

This is well-defined because we assume only that the loops are piecewise smooth. So for the two families of closed strings  $(P, f)$  and  $(Q, g)$  above, we can define a new family of closed strings by taking  $P * Q$  and composing  $\psi$  from  $(\Omega)$  with  $\star$ :  $(P * Q, \star\psi)$ .

So we essentially take a point in  $P * Q$  and send it to the concatenation of its associated tuple of loops.

We can now for  $[P, a, f] \in H'_{n_1+d}(LM)$  and  $[Q, b, g] \in H'_{n_2+d}(LM)$ , define a loop product  $\wedge$  as follows: first smooth  $f$  and  $g$  and make them transverse to  $\tilde{\Delta}$ . Then we form the pullback  $P * Q$ .

**Definition 5.3.** [3, Definition 4.2.1] Let  $j: P * Q \rightarrow P \times Q$  be the canonical maps. Then we have the pairing

$$\begin{aligned} \wedge: \mathbb{H}'_{n_1}(LM) \otimes \mathbb{H}'_{n_2}(LM) &\rightarrow \mathbb{H}'_{n_1+n_2}(LM) \\ [P, a, f] \wedge [Q, b, g] &= (-1)^{d(|a|+|b|)+\dim(P)|b|} [P * Q, j^*(a \times b), \star\psi] \end{aligned}$$

which is called the *Chas-Sullivan loop product*.

Note in particular, that if we disregard the cohomology element, the data consists of  $P * Q$  and the associated loops which makes it easy to think about loop products.

**Proposition 5.4.** *The loop product is associative and commutative.*

*Proof.* Associativity follows from associativity of the intersection product, the cup product and also, up to homotopy, of  $\star$ .

Now consider the map

$$Ev_1: I \times LM \times LM \rightarrow M \times M$$

given by  $Ev_1(t, \gamma_1, \gamma_2) = (\gamma_1(0), \gamma_2(t))$ . We can take the pullback

$$\begin{array}{ccc} \text{Map}(8_t, M) & \xrightarrow{\tilde{\Delta}_t} & I \times LM \times LM \\ \downarrow & & \downarrow Ev_1 \\ M & \xrightarrow{\Delta} & M \times M \end{array}$$

where  $\text{Map}(8_t, M) = \{(t, \gamma_1, \gamma_2) \mid \gamma_1(0) = \gamma_2(t)\}$ . We also have a map

$$comp_1: \text{Map}(8_t, M) \rightarrow LM$$

given by

$$comp_1(t, \gamma_1, \gamma_2) = \begin{cases} \gamma_2(2\theta), & \theta \in [0, \frac{t}{2}) \\ \gamma_1(2\theta - t), & \theta \in [\frac{t}{2}, \frac{t+1}{2}) \\ \gamma_2(2\theta - 1), & \theta \in [\frac{t+1}{2}, 1] \end{cases}$$

I.e, we essentially insert  $\gamma_1$  into  $\gamma_2$  at the point corresponding to  $t$ . Let also  $\tau$  denote the interchanging map,  $(\alpha, \beta) \mapsto (\beta, \alpha)$ .

$$\tau: LM \times_M LM \rightarrow LM \times_M LM.$$

We want now to take  $I \times P * Q$  and on  $\{0\} \times P * Q$  put  $\star\psi$  and on  $\{0\} \times P * Q$  put  $\star\tau\psi$ .

$$\begin{array}{ccc} \text{Map}(8_t, M) \times_{I \times LM \times LM} I \times P \times Q & \longrightarrow & I \times P \times Q \\ \downarrow \tilde{\psi} & & \downarrow \text{id} \times f \times g \\ \text{Map}(8_t, M) & \xrightarrow{\tilde{\Delta}_t} & I \times LM \times LM \end{array}$$

This pullback consists of pairs  $((t, \gamma_1, \gamma_2), (t, p, q))$  such that  $f(p) = \gamma_1$  and  $g(q) = \gamma_2$  and  $\gamma_1(0) = \gamma_2(t)$ , which is thus the same as tuples  $(t, p, q)$  such that  $f(p)(0) = g(q)(t)$ .

If  $(\gamma_1, \gamma_2) \in LM \times_M LM$ , then  $(0, p, q)$  and  $(1, p, q)$  are in the pullback, corresponding under  $\text{comp}_1 \circ \tilde{\psi}$  to  $\gamma_1 \star \gamma_2$  and  $\gamma_2 \star \gamma_1$ , respectively. So this gives a cobordism between

$$[P * Q, j^*(a \times b), \star\psi]$$

and

$$\begin{aligned} [P * Q, \tau^*(j^*(a \times b)), \star\tau\psi] &= (1)^{(\dim(P)-d-|a|)(\dim(Q)-d-|b|)} [P * Q, j^*(b \times a), \star\tau\psi] \\ &= (-1)^{(\dim(P)-d-|a|)(\dim(Q)-d-|b|)} [Q * P, j^*(b \times a), \star\psi] \end{aligned}$$

□

Merge the  
above two  
subsubsections

#### 5.1.4. The article's approach.

The idea to think about for the Chas-Sullivan product is to start with a  $p$ -chain  $x \in \Delta_p(LM)$  and a  $q$ -chain  $y \in \Delta_q(LM)$ . Then taking the intersection of the transverse chains  $\text{ev}_0 x$  and  $\text{ev}_0 y$ , which form a  $p$ - and  $q$ -chain in  $M$ , gives a  $(p+q-n)$ -chain  $z$  in  $M$ . Along this chain  $z$ , we can compose the loops of  $x$  and  $y$ , and we define  $x \wedge y$  to be this element of  $\Delta_{p+q-n}(LM)$ .

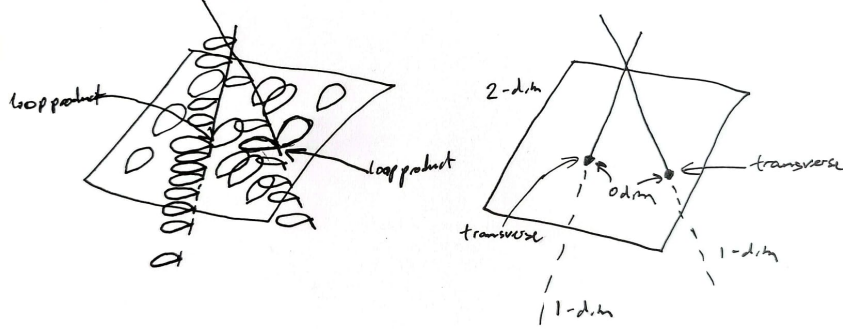


FIGURE 1. The transverse intersection of two 1-chains and a 2-chain in a 3-manifold giving a 0-chain as a loop product. [2, From Figure 2]

*Remark* (An orientation convention). [2, Remark 2.1]

Let  $i: K_1 \times K_2 \times \dots \times K_n \rightarrow M \times \dots \times M$  be a map such that  $i \pitchfork \Delta$ . Then  $i^{-1}(\Delta)$  is a submanifold of  $K_1 \times \dots \times K_n$  and taking the normal bundle  $N(i^{-1}(\Delta))$ , we orient it such that

$$[N(i^{-1}(\Delta))] i^* [N\Delta] = [K_1 \times \dots \times K_n].$$



Next, we will be introducing a grading on our homology soon, and therefore, we preemptively denote the  $(p - n)$ -chains of  $LM$  by  $(LM)_p$ , and let  $(LM)_* = \bigoplus_{p \geq 0} (LM)_p$ .

Now for any pair  $x: \Delta_p \rightarrow LM$  and  $y: \Delta_q \rightarrow LM$ , let  $\Delta_{x \wedge y} = j^{-1}(\Delta)$  where  $j$  is the map

$$j: \Delta_p \times \Delta_q \xrightarrow{\text{ev}_0 \times \text{ev}_0} M \times M$$

$$(u, v) \mapsto (\text{ev}_0 x(u), \text{ev}_0 y(v))$$

Then define  $x \wedge y: \Delta_{x \wedge y} \rightarrow ML$  by

$$(x \wedge y)(u, v)(*)(s) = \begin{cases} x(u)(*)(2s), & s \in [0, \frac{1}{2}] \\ y(v)(*)(2s - 1), & s \in [\frac{1}{2}, 1] \end{cases}$$

And we orient  $\Delta_{x \wedge y}$  by Remark 5.1.4.

Because of the grading chosen on  $(LM)_*$ , we then have that if  $x \in (LM)_p$  and  $y \in (LM)_q$ , then  $x$  is a  $(p + n)$  chain and  $y$  a  $(q + n)$  chain, so  $x \wedge y$  is a  $(p + q + n)$  chain, hence in  $(LM)_{p+q}$ , so  $\wedge$  defines a map  $(LM)_p \times (LM)_q \rightarrow (LM)_{p+q}$ .

**Definition 5.5** (Chas-Sullivan product  $\wedge$ ). The *Chas-Sullivan product*  $\wedge$  is a lift of the intersection product making the following diagram commute:

$$\begin{array}{ccc} H_p(LM) \otimes H_q(LM) & \xrightarrow{\wedge} & H_{p+q-n}(LM) \\ \downarrow \text{ev}_0 \otimes \text{ev}_0 & & \downarrow \text{ev}_0 \\ H_p(M) \otimes H_q(M) & \xrightarrow{\bullet} & H_{p+q-n}(M) \end{array}$$

We now explain the construction.

Recall the  $\varepsilon$ -neighborhood  $U_M$  of the diagonal in  $M \times M$  and now just pull this back along  $\text{ev}_0 \times \text{ev}_0$  to  $LM \times LM$ :

$$U_{CS} = (\text{ev}_0 \times \text{ev}_0)^{-1} U_M = \{(\gamma, \lambda) \in LM \times LM \mid |\gamma(0) - \lambda(0)| < \varepsilon\}.$$

Defining a retraction

$$R_{CS}: U_{CS} \rightarrow LM \times_M LM = \{(\gamma, \lambda) \in LM \times LM \mid \gamma(0) = \lambda(0)\} = (\text{ev}_0 \times \text{ev}_0)^{-1}(\Delta_M \subset M \times M)$$

by concatenating with a "geodesic stick" to connect the loops so that they form a "figure 8":

$$R_{CS}(\gamma, \lambda) = (\gamma, \lambda') \quad \text{with} \quad \lambda' = \overline{\gamma(0)\lambda(0)} \star \lambda \star \overline{\lambda(0)\gamma(0)}$$

where for  $x, y \in M$  with  $|x - y| < \rho$ ,  $\overline{xy}$  denotes the unique minimal geodesic path  $[0, 1] \rightarrow M$  from  $x$  to  $y$ . Figure 2 describes this intuitively.

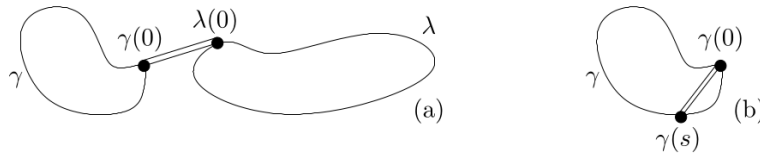


FIGURE 2. Figures/HGFHEIA.png

This is a lift of the retraction  $r: U_M \rightarrow M$  in the sense that

$$\begin{array}{ccc} U_{CS} & \xrightarrow{R_{CS}} & LM \times_M LM \\ \text{ev}_0 \times \text{ev}_0 \downarrow & & \downarrow \text{ev}_0 \\ U_M & \xrightarrow{r} & M \end{array}$$

commutes.

Pulling back  $\tau_M$  along  $\text{ev}_0 \times \text{ev}_0$  gives a cochain

$$\tau_{CS} := (\text{ev}_0 \times \text{ev}_0)^* \tau_M \in C^*(LM \times LM, LM \times LM - LM \times_M LM)$$

Finally, we define the Chas-Sullivan loop product on chains as follows:

**Definition 5.6** (Chas-Sullivan loop Product). The following sequence of chain maps induces the Chas-Sullivan product on homology:

$$\begin{aligned} \wedge: C_p(LM) \otimes C_q(LM) &\xrightarrow{\times} C_{p+q}(LM \times LM) \xrightarrow{[\tau_{CS} \cap]} C_{p+q-n}(U_{CS}) \\ &\xrightarrow{R_{CS}} C_{p+q-n}(LM \times_M LM) \xrightarrow{\text{concat}} C_{p+q-n}(LM). \end{aligned}$$

While this definition coincides with the Chas-Sullivan product in homology as described by Cohen-Jones, it is not necessarily clear how it coincides with the original geometric picture.

5.1.5. *Coproduct.* Define  $e_I: LM \times I \rightarrow M \times M$  by  $e_I(\gamma, s) = (\gamma(0), \gamma(s))$ . Set

$$U_{GH} = e_I^{-1}U_M = \{(\gamma, s) \in LM \times I \mid |\gamma(0) - \gamma(s)| < \varepsilon\},$$

and we have a commutative diagram

$$\begin{array}{ccccc} U_{GH} & \xrightarrow{R_{GH}} & \mathcal{F} = \{(\gamma, s) \in LM \times I \mid \gamma(0) = \gamma(s)\} & \hookrightarrow & LM \times I \\ \downarrow e_I & & \downarrow e_I & & \downarrow \\ U_M & \xrightarrow{r} & \Delta M & \hookrightarrow & M \times M \end{array}$$

defining a retraction map  $R_{GH}$  by concatenating with a geodesic stick to force self-intersection:

$$R_{GH}(\gamma, s) = (\gamma', s) \quad \text{with} \quad \gamma' = \gamma[0, s] \star \overline{\gamma(s)\gamma(0)} \star_s \overline{\gamma(0)\gamma(s)} \star [s, 0]$$

where the parametrization is chosen so that the concatenated loop passes through  $\gamma(0)$  at time  $s$ ; if  $s = 0$  or  $1$  as in the case  $\gamma(0) = \gamma(s)$  to begin with, the geodesic sticks are of length 0.

**Definition 5.7** (Goresky-Hingston-Sullivan coproduct). The following sequence of chain maps is a chain model for the Goresky-Hingston-Sullivan coproduct:

$$\begin{aligned} \vee: C_p(LM, M) &\xrightarrow{\times I} C_{p+1}(LM \times I, LM \times \partial I \cup M \times I) \xrightarrow{[\tau_{GH} \cap]} C_{p+1-n}(U_{GH}, LM \times \partial I \cup M \times I) \\ &\xrightarrow{R_{GH}} C_{p+1-n}(\mathcal{F}, LM \times \partial I \cup M \times I) \xrightarrow{\text{cut}} C_{p+q-n}(LM \times LM, M \times LM \cup LM \times M) \end{aligned}$$

This induces a well-defined degree  $1 - n$  map

$$\vee: H_p(LM, M) \rightarrow H_{p+1-n}(LM \times LM, M \times LM \cup LM \times M).$$

## 5.2. Computation via geometric intersection.

**Proposition 5.8.** [6, Propositions 3.1 and 3.7]

- (1) If  $Z_1: \Sigma_1 \rightarrow LM$  and  $Z_2: \Sigma_2 \rightarrow LM$  are smooth cycles with the property that the maps  $\text{ev}_0 \circ Z_1: \Sigma_1 \rightarrow M$  and  $\text{ev}_0 \circ Z_2: \Sigma_2 \rightarrow M$  are transverse, then the loop product

$$Z_1 \wedge Z_2 = (Z_1 \star Z_2)|_{\Sigma_1 \times_{\text{ev}_0} \Sigma_2} \in H_*(LM)$$

is the concatenation of the loops of  $Z_1$  and  $Z_2$  along the locus of the basepoint-intersections  $\Sigma_1 \times_{\text{ev}_0} \Sigma_2 \subset \Sigma_1 \times \Sigma_2$ , oriented as stated in [6]

- (2) If  $Z: (\Sigma, \Sigma_0) \rightarrow (LM, M)$  is a smooth relative cycle with the property that the restriction of  $e_I \circ (Z \times I): \Sigma \times I \rightarrow M \times M$  to  $(\Sigma - \Sigma_0) \times (0, 1)$  is transverse to the diagonal, then

$$\vee Z = \text{cut} \circ (Z \times I)|_{\overline{\Sigma_\Delta}} \in H_*(LM \times LM, M \times LM \cup LM \times M)$$

for  $\overline{\Sigma_\Delta}$  the closure in  $\Sigma \times I$  of the locus of basepoint self-intersecting loops  $\Sigma_\Delta \subset (\Sigma - \Sigma_0) \times (0, 1)$ , oriented as stated in [6].

*Note.* Here  $\Sigma_1 \times_{\text{ev}_0} \Sigma_2$  is the pullback

$$\begin{array}{ccc} \Sigma_1 \times_{\text{ev}_0} \Sigma_2 & \longrightarrow & \Sigma_2 \\ \downarrow & & \downarrow \text{ev}_0 \circ Z_2 \\ \Sigma_1 & \xrightarrow{\text{ev}_0 \circ Z_1} & M \end{array}$$

5.2.1. *Lens spaces.* Consider  $S^3 \subset \mathbb{C}^2$  as  $(r, \theta) = ((r_1, \theta_1), (r_2, \theta_2))$  with  $\theta_i \in \mathbb{R}/\mathbb{Z}$  and  $r_i \geq 0$ , satisfying  $r_1^2 + r_2^2 = 1$ . Here we think of  $S^3$  as  $\{r_1 e^{i\theta_1}, r_2 e^{i\theta_2}\}$  with  $r_1^2 + r_2^2 = 1$ .

In particular, when  $r_i$  is zero,  $(r_i, \theta_i) = 0$ .

The lens space  $\mathcal{L}_{p,q}$ , for  $p, q$  coprime, is the quotient space  $S^3/\mathbb{Z}/p$  with the  $\mathbb{Z}/p$  action defined by

$$((r_1, \theta_1), (r_2, \theta_2)) \mapsto \left( \left( r_1, \theta_1 + \frac{1}{p} \right), \left( r_2, \theta_2 + \frac{q}{p} \right) \right).$$

There is a residual torus action on the lens space by

$$\begin{aligned} \alpha: (S^1 \times S^1) \times \mathcal{L}_{p,q} &\rightarrow \mathcal{L}_{p,q}, \\ ((s, t), (r, \theta)) &\mapsto \left( \left( r_1, \theta_1 + \frac{s}{p} \right), \left( r_2, \theta_2 + \frac{sq}{p} + t \right) \right) \end{aligned}$$

Using this residual torus action, we define cycles  $Z_{l,m}$  for pairs of integers  $(l, m)$  as follows: let

$$\delta_{l,m}: S^1 \rightarrow S^1 \times S^1$$

be the torus knot  $t \mapsto (lt, mt)$  of slope  $\frac{l}{m}$ . We can combine this loop with the action  $\alpha$  of the torus on  $\mathcal{L}_{p,q}$  to get a family

$$\begin{aligned} Z_{l,m}: \mathcal{L}_{p,q} &\rightarrow L\mathcal{L}_{p,q} \\ (r, \theta) &\mapsto \left[ \gamma_{r,\theta}^{l,m}: t \mapsto \alpha(\delta_{l,m}(t), (r, \theta)) \right] \end{aligned}$$

associated to each point  $(r, \theta)$  in the lens space, the loop  $\gamma_{r,\theta}^{l,m}$  is based at this point and follows the image of  $\delta_{l,m}$  along the torus action.

That is, the loop is defined by

$$\gamma_{r,\theta}^{l,m}(t) = \left( \left( r_1, \theta_1 + \frac{lt}{p} \right), \left( r_2, \theta_2 + \frac{ltq}{p} + mt \right) \right).$$

Note now that Lens spaces are manifolds, and in particular,  $\mathcal{L}_{p,q}$  are compact oriented 3-manifolds, so we can pick a fundamental class  $[\mathcal{L}_{p,q}]$ .

Denote by

$$Z_{l,m} = (Z_{l,m})_* [\mathcal{L}_{p,q}] \in H_3(L\mathcal{L}_{p,q})$$

the associated homology class. Suppose we now postcompose with  $\text{ev}_0$ , i.e., we look at the class

$$(\text{ev}_0)_* Z_{l,m} \in H_3(\mathcal{L}_{p,q})$$

we note that the composition  $\text{ev}_0 \circ Z_{l,m}$  is just the identity, so this just sends  $[\mathcal{L}_{p,q}]$  to itself. Thus also  $Z_{l,m} \in H_3(L\mathcal{L}_{p,q})$  is non-trivial.

is this the right interpretation. Otherwise, how is  $Z_{l,m}$  in  $H_3(L\mathcal{L}_{p,q})$ ?

**5.2.2. The loop product of the classes  $Z_{l,m}$ .** Let  $Z_1 = Z_{l_1,m_1}$  and  $Z_2 = Z_{l_2,m_2}$ . Since  $\text{ev}_0 \circ Z_i$  is the identity for both  $i$ ,  $\text{ev}_0 \circ Z_1$  is transverse to  $\text{ev}_0 \circ Z_2$ . Furthermore, the locus of basepoint-intersections is the pullback

$$\begin{array}{ccc} \mathcal{L}_{p,q} \times_{\text{ev}_0} \mathcal{L}_{p,q} & \longrightarrow & \mathcal{L}_{p,q} \\ \downarrow & & \downarrow \text{ev}_0 \circ Z_2 \\ \mathcal{L}_{p,q} & \xrightarrow{\text{ev}_0 \circ Z_1} & \mathcal{L}_{p,q} \end{array}$$

so

$$\begin{aligned} \mathcal{L}_{p,q} \times_{\text{ev}_0} \mathcal{L}_{p,q} &= \{((r_1, \theta_1), (r_2, \theta_2)) \in \mathcal{L}_{p,q} \times \mathcal{L}_{p,q} \mid (r_1, \theta_1) = \text{ev}_0 Z_1(r_1, \theta_1) = \text{ev}_0 Z_2(r_2, \theta_2) = (r_2, \theta_2)\} \\ &= \Delta \mathcal{L}_{p,q} \end{aligned}$$

Hence using Proposition 5.8, we obtain that  $Z_{l_1,m_1} \wedge Z_{l_2,m_2}$  sends each point  $(r, \theta)$  of  $\mathcal{L}_{p,q} \cong \Delta \mathcal{L}_{p,q}$  to the concatenated loop  $Z_{l_1,m_1} \star Z_{l_2,m_2}$  based at  $(r, \theta)$ , where  $\star$  is the concatenation of the loops in the image at their common basepoint.

**Proposition 5.9.** *The Chas-Sullivan loop product of the classes  $Z_{l,m} \in H_3(L\mathcal{L}_{p,q})$  defined above is given by summing the indices:*

$$Z_{l_1,m_1} \wedge Z_{l_2,m_2} = Z_{l_1+l_2, m_1+m_2}.$$

*Proof.* By the above considerations and Proposition 5.8, have

$$Z_{l_1,m_1} \wedge Z_{l_2,m_2} = (Z_{l_1,m_1} \star Z_{l_2,m_2})|_{\Delta \mathcal{L}_{p,q}} : \mathcal{L}_{p,q} \cong \Delta \mathcal{L}_{p,q} \rightarrow L\mathcal{L}_{p,q}$$

where  $\star$  is the concatenation of the loops in the image at their common basepoint, i.e., it is the map  $\mathcal{L}_{p,q} \rightarrow L\mathcal{L}_{p,q}$  sending  $(r, \theta) \mapsto \gamma_{r,\theta}^{l_1,m_1} * \gamma_{r,\theta}^{l_2,m_2}$  which is the image under the torus action of the concatenated loops  $(l_1, m_1)$  and  $(l_2, m_2)$  in the torus. Concatenation corresponds to addition in the fundamental group, so the concatenation becomes  $(l_1, m_1) * (l_2, m_2) = (l_1 + l_2, m_1 + m_2)$ , so  $\gamma_{r,\theta}^{l_1,m_1} * \gamma_{r,\theta}^{l_2,m_2} = \gamma_{r,\theta}^{l_1+l_2, m_1+m_2}$ . This homotopy descends to the lens space, so up to homotopy in the codomain,  $Z_{l_1,m_1} \wedge Z_{l_2,m_2} = Z_{l_1+l_2, m_1+m_2}$ , and thus the classes agree in  $H_3(L\mathcal{L}_{p,q})$ .  $\square$

Now that we have determined the loop product of the classes, we turn to coproducts.

5.2.3. *B-classes.* Recall that the coproduct is a degree  $1-3 = -2$  map on  $H_*(L\mathcal{L}_{p,q}, \mathcal{L}_{p,q})$ :

$$\vee: H_3(L\mathcal{L}_{p,q}, \mathcal{L}_{p,q}) \rightarrow H_1(L\mathcal{L}_{p,q} \times L\mathcal{L}_{p,q}, \mathcal{L}_{p,q} \times L\mathcal{L}_{p,q} \cup L\mathcal{L}_{p,q} \times \mathcal{L}_{p,q})$$

The coproduct of the classes  $Z_{l,m}$  will be given in terms of *B-classes* in the target.

Let  $\lambda: S^1 \rightarrow \mathcal{L}_{p,q}$  be the loop defined by  $\lambda(t) = \left(1, \frac{t}{p}\right)$  tracing the points  $(r, \theta) \in \mathcal{L}_{p,q}$  with  $(r_2, \theta_2) = 0$ . Then  $\lambda$  is a generator of  $\pi_1 \mathcal{L}_{p,q} \cong \mathbb{Z}/p$ : it has order  $p$  as can be seen by lifting it to  $S^3$ .

Note that

$$Z_{1,0}((1,0),0) = \gamma_{((1,0),0)}^{1,0} = \left[ t \mapsto \left(1, \frac{t}{p}\right), 0 \right] = \lambda$$

Projecting a path from  $((1,0),0)$  to  $(0,(1,0))$  under  $Z_{1,0}$  gives a free homotopy from  $\gamma_{((1,0),0)}^{1,0}$  to  $\gamma_{(0,(1,0))}^{1,0}$ . Note that

$$\gamma_{(0,(1,0))}^{1,0} = \left[ t \mapsto \left(0, \left(1, \frac{qt}{p}\right)\right) \right] = (\lambda')^{*q}$$

for  $\lambda': S^1 \rightarrow \mathcal{L}_{p,q}$  defined by  $\lambda'(t) = \left(0, \left(1, \frac{t}{p}\right)\right)$ .

**Definition 5.10.** Define the 1-cycles  $B_{k,k'}$  and  $B'_{k,k'}$  in  $\mathcal{L}_{p,q}$  as follows: let  $\lambda_s: S^1 \rightarrow \mathcal{L}_{p,q}$  be the rotation of  $\lambda$ , based at  $\lambda(s)$ :

$$\lambda_s(t) = \lambda(s+t).$$

Similarly for  $\lambda'$ . Define

$$\begin{aligned} B_{k,k'}: S^1 &\rightarrow L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q} \subset L\mathcal{L}_{p,q} \times L\mathcal{L}_{p,q}, \\ s &\mapsto \left( (\lambda_s)^{*k}, (\lambda_s)^{*k'} \right) \end{aligned}$$

We also denote by  $B_{k,k'} \in H_1(L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q})$  or  $H_1(L\mathcal{L}_{p,q} \times L\mathcal{L}_{p,q})$  the associated homology class  $(B_{k,k'})_*[S^1]$ . Then the evaluation  $(ev_0)_*: H_1(L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q}) \rightarrow H_1(\mathcal{L}_{p,q})$  takes

$$B_{k,k'} = (B_{k,k'})_*[S^1] \mapsto (ev_0 \circ B_{k,k'})_*[S^1] = \lambda_*[S^1] = [\lambda]$$

Define  $B'_{k,k'}$  in the same way by replacing  $\lambda$  by  $\lambda'$  above.

**Lemma 5.11.** [8, Lemma 2.6] Let  $B'_{k,k'}: S^1 \rightarrow L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q}$  be the family of figure eights based at the points of  $\lambda'$  defined by  $B'_{k,k'}(s) = \left( (\lambda'_s)^{*k}, (\lambda'_s)^{*k'} \right)$ . Then

$$B_{k,k'} = qB'_{qk,qk'} \in H_1(L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q})$$

is the sum of  $q$  copies of the class  $B'_{qk,qk'}$ .

*Proof.* As above, projecting a path from  $((1,0),0)$  to  $(0,(1,0))$  under  $Z_{1,0}$  in  $\mathcal{L}_{p,q}$  gives an explicit free homotopy  $\lambda \simeq_h (\lambda')^{*q}: S^1 \rightarrow \mathcal{L}_{p,q}$ . Let  $h: S^1 \times I \rightarrow \mathcal{L}_{p,q}$  be the evaluation of  $Z_{1,0}$  along the line  $((\sqrt{1-\tau^2}, 0), (\tau, 0))$ ,  $\tau \in [0, 1]$ , giving the formula

$$h(s, t) = \left( \left( \sqrt{1-\tau^2}, \frac{s}{p} \right), \left( \tau, \frac{qs}{p} \right) \right) \in \mathcal{L}_{p,q}.$$

Then there is a lift  $H: S^1 \times I \rightarrow L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} L\mathcal{L}_{p,q}$  of  $h$  consisting of loops based at the value of  $h$ , defined by

$$H(s, \tau) = \left( \left[ t \mapsto \left( \left( \sqrt{1-\tau^2}, \frac{s+kt}{p} \right) \right), \left( \tau, \frac{q(s+kt)}{p} \right) \right], \left[ t \mapsto \left( \left( \sqrt{1-\tau^2}, \frac{s+k't}{p} \right), \left( \tau, \frac{q(s+k't)}{p} \right) \right) \right] \right)$$

which starts at

$$H(s, 0) = \left( \left[ t \mapsto \left( \left( 1, \frac{s+kt}{p} \right), 0 \right) \right], \left[ t \mapsto \left( \left( 1, \frac{s+k't}{p} \right), 0 \right) \right] \right) = ((\lambda_s)^{\star k}, (\lambda_s)^{\star k'}) = B_{k,k'},$$

and similarly,

$$H(s, 1) = \left( \left[ t \mapsto \left( 0, \left( 1, \frac{q(s+kt)}{p} \right) \right) \right], \left[ t \mapsto \left( 0, \left( 1, \frac{q(s+k't)}{p} \right) \right) \right] \right) = ((\lambda'_{qs})^{\star qk}, (\lambda'_{qs})^{\star qk'})$$

which, in homology, represents  $qB'_{qk,qk'}$ .  $\square$

**Lemma 5.12.** [8, Lemma 2.7] *We have that*

- (1)  $B_{k,k'} = B_{h,h'} \in H_1(L\mathcal{L}_{p,q} \times L\mathcal{L}_{p,q})$  if and only if  $k = h \pmod p$  and  $k' = h' \pmod p$ .
- (2) *The relative classes*

$$\{B_{k,k'}\}_{\substack{0 < k < p \\ 0 < k' < p}} \in H_1(L\mathcal{L}_{p,q} \times L\mathcal{L}_{p,q}, \mathcal{L}_{p,q} \times L\mathcal{L}_{p,q} \cup L\mathcal{L}_{p,q} \times \mathcal{L}_{p,q})$$

are linearly independent over  $\mathbb{Z}/p$ .

*Proof.*  $\square$

**Proposition 5.13.** [8, Proposition 2.8] *The coproduct of the classes  $Z_{l,m} \in H_3(L\mathcal{L}_{p,q}, \mathcal{L}_{p,q})$  with  $l, m \geq 0$  is given by the formula*

$$\vee Z_{l,m} = \sum_{\substack{0 < k < l \\ k, (l-k) \not\equiv 0 \pmod p}} B_{k,l-k} + q' \sum_{\substack{0 < k < ql+pm \\ k, (l-kq') \not\equiv 0 \pmod p}} B_{kq', l-kq'}$$

where  $q'$  is the multiplicative inverse of  $q \pmod p$ .

*Proof.* We want to make use of (2) in Proposition 5.8.

To do this, we need  $e_I \circ (Z \times I) : \mathcal{L}_{p,q} \times I \rightarrow \mathcal{L}_{p,q} \times \mathcal{L}_{p,q}$  restricted to  $(L\mathcal{L}_{p,q} - \mathcal{L}_{p,q}) \times (0, 1)$  to be transverse to the diagonal, where  $e_I$  evaluates the loops at 0 and  $s \in (0, 1) \subset I$  (here  $\mathcal{L}_{p,q} \subset L\mathcal{L}_{p,q}$  is the locus of constant loops).

Recall that  $Z_{l,m}$  takes  $(r, \theta)$  to  $\left[ \gamma_{r,\theta}^{l,m} : t \mapsto \alpha(\delta_{l,m}(t), (r, \theta)) \right]$ . If  $(l, m) = (0, 0)$ , then  $\delta_{0,0}$  is constant at  $(0, 0)$  and so  $\alpha$  is constant at  $(r, \theta)$ , so  $Z_{0,0}$  maps  $(r, \theta)$  to the constant loop at  $(r, \theta)$ . Thus  $Z_{0,0} = 0 \in H_3(L\mathcal{L}_{p,q}, \mathcal{L}_{p,q})$ .

Conversely, if  $Z_{l,m}(r, \theta)$  is constant then  $\left[ \gamma_{r,\theta}^{l,m} : t \mapsto \left( \left( r_1, \theta_1 + \frac{lt}{p} \right), \left( r_2, \theta_2 + \frac{ltq}{p} + mt \right) \right) \right]$  is constant at  $(r, \theta)$ , so  $l$  and  $m$  must be 0, hence if  $(l, m) \neq (0, 0)$ ,  $Z_{l,m}$  has no constant cycles in its image.

We can assume that  $(l, m) \neq (0, 0)$  and work with  $(\Sigma, \Sigma_0) = (\mathcal{L}_{p,q}, \emptyset)$ .

*Transversality:* represent the homology class of  $Z_{l,m}$  by the homotopic family  $\tilde{Z}_{l,m} : \mathcal{L}_{p,q} \rightarrow L\mathcal{L}_{p,q}$  defined by  $\tilde{Z}_{l,m}(r, \theta) = \tilde{\gamma}_{r,\theta}^{l,m}$  for  $\tilde{\gamma}_{r,\theta}^{l,m} : S^1 \rightarrow \mathcal{L}_{p,q}$  the loop based at  $(r, \theta)$  given by

$$\tilde{\gamma}_{r,\theta}^{l,m}(t) = \left( \left( \tilde{r}_1(t), \theta_1 + \frac{lt}{p} \right), \left( \tilde{r}_2(t), \theta_2 + \frac{ql+pm}{p}t \right) \right),$$

where  $(\tilde{r}_1(t), \tilde{r}_2(t))$  is a deformation of  $(r_1, r_2)$  with  $(\tilde{r}_1(t), \tilde{r}_2(t)) = (r_1, r_2)$  only for  $r_1 = 0$  or  $r_2 = 0$ , or when  $t = 0$  or  $1$ . For example, we can let

$$\tilde{r}_1(t) = \begin{cases} (1-2t)r_1 + 2tr_1^2, & t \in [0, \frac{1}{2}] \\ r_1^2(2-2t) + r_1(2t-1), & t \in [\frac{1}{2}, 1] \end{cases}$$

and  $\tilde{r}_2(t) = \sqrt{1 - \tilde{r}_1(t)^2}$ .

We can visualize this as follows: foliate  $S^4 \cong \mathbb{R}^3 \cup \{\infty\}$  by tori. Then for fixed radii, the angle coordinates trace out a torus. Then  $\mathbb{Z}/p$  still acts on this torus, and it is on this quotient torus, that  $\gamma_{r,\theta}^{l,m}$  lives. So understanding self-intersections amounts to understanding self-intersections on this quotient torus of the torus knot one is interested in.

For example, if  $m = 0$ , then for  $l \geq 1$ ,  $Z_{l,m}(r, \theta)$  has  $l - 1$  self-intersections.

But for large  $l$  and  $m$ , these loops will have many self-intersections. What  $\tilde{Z}_{l,m}$  does is that it makes it so that, as we vary  $t$ , we also vary the radius such that only the torus knots corresponding to the endpoints live on the original torus knot corresponding to  $Z_{l,m}$ . See Figure 3

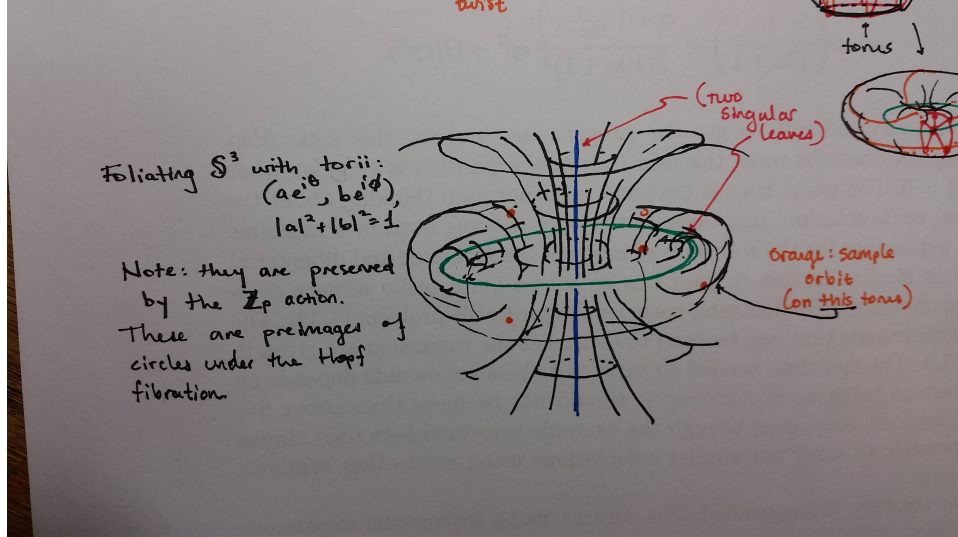


FIGURE 3. Figures/foliating-tori.jpg

Then the map  $e_I \circ (\tilde{Z}_{l,m} \times \text{id})|_{\mathcal{L}_{p,q} \times (0,1)}$  intersects the diagonal when  $\tilde{\gamma}_{r,\theta}^{l,m}$  has a self-intersection  $\tilde{\gamma}_{r,\theta}^{l,m}(0) = \tilde{\gamma}_{r,\theta}^{l,m}(t)$  for some  $t \in (0, 1)$ .

Since the  $r$  coordinates must match, such a self-intersection can only happen for  $r_1 = 0$  or  $r_2 = 0$  since otherwise  $\tilde{r}_i(t) \neq \tilde{r}_i(0) = r_i$ .

For  $r_2 = 0$ , we have that  $\tilde{r}_1(t) = r_1 = 1$  and  $\tilde{r}_2(t) = r_2 = 0$ , and

$$\tilde{\gamma}_{r,\theta}^{l,m}(t) = \left( \left( 1, \theta_1 + \frac{lt}{p} \right), 0 \right)$$

The first angle coincides with  $\theta_1$  precisely when  $\frac{lt}{p} \in \frac{1}{l}\mathbb{Z}$ , i.e., when  $t \in \frac{1}{l}\mathbb{Z} \cap (0, 1)$ .

When  $r_1 = 0$ , we get

$$\tilde{\gamma}_{r,\theta}^{l,m}(t) = \left(0, \left(1, \theta_2 + \frac{ql+pm}{p}t\right)\right)$$

Since  $\gcd(p, q) = 1$ , Bezout gives that  $\frac{k}{p} = 0$  in the second coordinate, so the second angle coincides with  $\theta_2$  whenever  $\frac{ql+pm}{p}t \in \frac{1}{p}\mathbb{Z}$ .

This yields the following parameters:

$$\begin{cases} 0 < t = \frac{a}{l} < 1, \text{ for some } a \in \mathbb{N}, & r_2 = 0 \\ 0 < t = \frac{b}{ql+pm} < 1 \text{ for some } b \in \mathbb{N}, & r_1 = 0. \end{cases}$$

So the locus of self-intersections of  $\tilde{Z}_{l,m} \times \text{id}|_{\mathcal{L}_{p,q} \times (0,1)}$  is

$$\Sigma_{\Delta} = (\lambda \times I_1) \cup (\lambda' \times I_2) \subset \mathcal{L}_{p,q} \times (0,1)$$

where  $I_1 = \{\frac{1}{l}, \dots, \frac{l-1}{l}\}$ ,  $I_2 = \{\frac{1}{ql+pm}, \dots, \frac{ql+pm-1}{ql+pm}\}$ , and  $\lambda, \lambda'$  are the loops parametrizing the points with  $r_2 = 0$  and  $r_1 = 0$ , respectively.

Note that  $\lambda$  and  $\lambda'$  correspond to the two degenerate cases of tori in the foliation.

We need to check transversality at these points.

Note that  $e_I \circ (\tilde{Z}_{l,m} \times \text{id})$  takes points with  $r_i$  coordinates 0 to points of the same form in the diagonal.

□



**5.3. A new operation.** Consider the 3-simplex  $\Delta^3 = \{(x_1, x_2, x_3) \in \mathbb{R}^3 \mid 0 \leq x_1 \leq x_2 \leq x_3 \leq 1\}$ , and consider the homology group  $H_3(\Delta^3, \partial\Delta^3) \cong H_3(D^3, S^2)$ , so

$$H_3(\Delta^3/\partial\Delta^3) \cong H_3(D^3, S^2) \cong \mathbb{Z}.$$

We want to see if we can construct an interesting homomorphism

$$H_3(L\mathcal{L}_{p,q}) \rightarrow H_0(L\mathcal{L}_{p,q}) \cong \mathbb{Z}^p$$

By the above, we can consider "products" of the form

$$H_3(L\mathcal{L}_{p,q}) \otimes H_3(\Delta^3/\partial\Delta^3) \rightarrow H_0(L\mathcal{L}_{p,q})$$

or more generally,

$$H_p(LM) \otimes H_q(\Delta^3/\partial\Delta^3) \rightarrow H_{p+q-2n}(LM)$$

which is only really interesting for  $q = 0, 3$ .

Let  $E: LM \times \Delta^3/\partial\Delta^3 \rightarrow M^4$  be defined by  $E(\gamma, (x_1, x_2, x_3)) = (\gamma(0), \gamma(x_2), \gamma(x_1), \gamma(x_3))$ . Define a map  $\Delta \times \Delta: M^2 \hookrightarrow M^4$  by  $\Delta \times \Delta(m, n) = (m, m, n, n)$ . Form the pullback

$$\begin{array}{ccc} LM \times_{M^4} \Delta^3/\partial\Delta^3 & \longrightarrow & LM \times \Delta^3/\partial\Delta^3 \\ \downarrow & & \downarrow E \\ M^2 & \xrightarrow{\Delta \times \Delta} & M^4 \end{array}$$

This pullback consists of loops  $\gamma$  for which there exist some  $0 < x_1 < x_2 < x_3 < 1$  such that  $\gamma(0) = \gamma(x_2)$  and  $\gamma(x_1) = \gamma(x_3)$ .

On this space, we define an operation

$\Upsilon: LM \times_{M^4} \Delta^3/\partial\Delta^3 \rightarrow LM$  given by concatenating the loop as shown in the figure

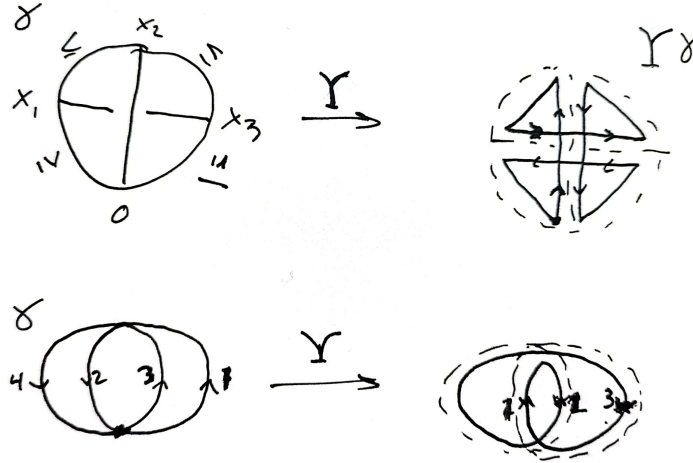


FIGURE 4.  $\Upsilon$  of a loop  $\gamma$

(or  $\Upsilon$  could potentially be some other operation).

Need to reference  
this last  
isomorphism

Now similarly to the construction of the coproduct, we can define a map  $LM \times \Delta^3/\partial\Delta^3 \rightarrow LM \times_{M^4} \Delta^3/\partial\Delta^3$  by, for an element  $(\gamma, (x_1, x_2, x_3))$ , inserting a geodesic stick between  $\gamma(0)$  and  $\gamma(x_2)$  as well as another geodesic stick between  $\gamma(x_1)$  and  $\gamma(x_3)$ , and then forming the desired loop by concatenating the different parts.

To make this precise, let us start by considering the diagonal embedding  $\Delta \times \Delta: M \times M \hookrightarrow M^2 \times M^2$ . Its normal bundle is isomorphic to the tangent bundle  $T(M \times M) \cong TM \oplus TM$ . Again identify  $T(M \times M)$  with  $T(M \times M)_\varepsilon$ ,  $\varepsilon \ll \rho$ ,  $\rho$  the injectivity radius of  $M \times M$ .

Then the map

$$\nu_{M \times M}: T(M \times M) \hookrightarrow M^4 \quad \nu_{M \times M}((x, v), (y, u)) = (x, \exp_x v, y, \exp_y u)$$

gives a tubular neighborhood of  $\Delta \times \Delta$ , with image the  $\varepsilon$ -image of the diagonal

$$\nu_{M \times M}: T(M \times M) \xrightarrow{\cong} U_1 = \{(x, x', y, y') \mid |x - x'|, |y - y'| < \varepsilon\}$$

and under this identification, the bundle projection map  $T(M \times M) \rightarrow M \times M$  becomes the retraction  $r: U_1 \rightarrow M \times M$  by  $r(x, x', y, y') = (x, y)$ .

Let  $\tau_{M \times M}$  be the image of a cochain representative for the Thom class for  $T(M \times M)$  under the quasi-isomorphism

$$C^{2n}(T(M \times M), T(M \times M) - M \times M) \xrightarrow{\cong} C^{2n}(M^4, M^4 - \Delta \times \Delta(M^2))$$

Now let

$$U_2 = E^{-1}(U_1) = \{(\gamma, (x_1, x_2, x_3)) \mid |\gamma(0) - \gamma(x_2)|, |\gamma(x_1) - \gamma(x_3)| < \varepsilon\}$$

and set  $\tau_{\Delta^3} = E^*(\tau_{M \times M})$ .

On this neighborhood, we can concatenate with the desired geodesic sticks, so we obtain a retraction  $R: U_2 \rightarrow LM \times_{M^4} \Delta^3/\partial\Delta^3$  sending

$$R(\gamma, (x_1, x_2, x_3)) = (\gamma', (x_1, x_2, x_3))$$

details

where  $\gamma'$  is the desired loop such that the following diagram commutes:

$$\begin{array}{ccccc} U_2 & \xrightarrow{R} & LM \times_{M^4} \Delta^3/\partial\Delta^3 & \hookrightarrow & LM \times \Delta^3/\partial\Delta^3 \\ \downarrow E & & \downarrow E & & \downarrow E \\ U_1 & \xrightarrow{r} & \Delta(M \times M) & \hookrightarrow & M^4 \end{array}$$

Now define the following operation composite:

$$\begin{aligned} \wedge_{\Delta^3}: C_p(LM) \otimes C_q(\Delta^3/\partial\Delta^3) &\xrightarrow{\times} C_{p+q}(LM \times \Delta^3/\partial\Delta^3) \xrightarrow{[\tau_{\Delta^3} \cap]} C_{p+q-2n}(U_2) \\ &\xrightarrow{R} C_{p+q-2n}(LM \times_M \Delta^3/\partial\Delta^3) \xrightarrow{\Upsilon} C_{p+q-2n}(LM). \end{aligned}$$

where the middle map  $[\tau_{\Delta^3} \cap]$  is defined as the composite

$$\begin{aligned} [\tau_{\Delta^3} \cap]: C_*(LM \times \Delta^3/\partial\Delta^3) &\rightarrow C_*(LM \times \Delta^3/\partial\Delta^3, LM \times \Delta^3/\partial\Delta^3 - LM \times_M \Delta^3/\partial\Delta^3) \\ &\xrightarrow{\sim} C_*(U_2, U_2 - LM \times_M \Delta^3/\partial\Delta^3) \xrightarrow{\tau_{\Delta^3} \cap} C_{*-2n}(U_2) \end{aligned}$$

Note that for  $A \in C_*(LM \times \Delta^3/\partial\Delta^3)$ ,  $[\tau_{\Delta^3} \cap](A) = \tau_{\Delta^3} \cap \rho(A)$  where  $\rho: C_*(LM \times \Delta^3/\partial\Delta^3) \rightarrow C_*(LM \times \Delta^3/\partial\Delta^3)$  is a chain map which subdivides simplices in such a way that  $\rho(A)$  is homologous to  $A$  and every simplex  $\sigma$  in  $\rho(A)$  has support in either  $U_2$  or

$LM \times \Delta^3/\partial\Delta^3 - U_{2,\varepsilon_0}$ , and hence  $\tau_{\Delta^3} \cap \rho(A)$  has support in  $U_2$ . Capping with the Thom class then kills all the simplices with support in  $LM \times \Delta^3/\partial\Delta^3 - U_{2,\varepsilon_0}$  (Cf. [6]).

Hence, for example, we obtain a product

$$\wedge_{\Delta^3}: H_3(L\mathcal{L}_{p,q}) \otimes H_3(\Delta^3/\partial\Delta^3) \cong H_3(L\mathcal{L}_{p,q}) \rightarrow H_0(L\mathcal{L}_{p,q}) \cong \mathbb{Z}^p$$

Reference for  
 $H_0(L\mathcal{L}_{p,q}) \cong \mathbb{Z}^p$

Consider now the classes  $Z_{l,m}$  from before.

We are interested in whether  $Z_{l,m}$  has transverse self-intersections so as to compute  $\Upsilon Z_{l,m}$ .

Now,  $Z_{l,m}$  maps  $(r, \theta)$  to

$$\gamma_{r,\theta}^{l,m}(t) = \left( \left( r_1, \theta_1 + \frac{lt}{p} \right), \left( r_2, \theta_2 + \frac{ltq}{p} + mt \right) \right).$$

As before, we could also replace  $Z_{l,m}$  with the homotopic  $\tilde{Z}_{l,m}$  given by

$$\tilde{\gamma}_{r,\theta}^{l,m}(t) = \left( \left( \tilde{r}_1(t), \theta_1 + \frac{lt}{p} \right), \left( \tilde{r}_2(t), \theta_2 + \frac{ql + pm}{p}t \right) \right)$$

For this to have  $\tilde{\gamma}_{r,\theta}^{l,m}(x_2) = \tilde{\gamma}_{r,\theta}^{l,m}(0)$ , with  $x_2 \in (0, 1)$ , we must have that  $\tilde{r}_i(t) = r_i$ , but  $r_i = \tilde{r}_i(0) \neq \tilde{r}_i(t)$  if  $r_i \neq 0, 1$ , hence as before, it can only coincide when  $r_1$  or  $r_2$  is zero.

Let us work out an explicit example.

Suppose  $(l, m) = (1, 2)$ , so if  $r_1 = 0$ ,

$$\tilde{Z}_{l,m}(0, \theta_1, 1, \theta_2) = \tilde{\gamma}_{r,\theta}^{1,2}(t) = \left( 0, \left( 1, \theta_2 + \frac{q+2p}{p}t \right) \right).$$

This gives the self-intersections  $\frac{q+2p}{p}t \in \frac{q}{p}\mathbb{Z}$ , i.e.,  $t \in \frac{q}{q+2p}\mathbb{Z} \cap (0, 1)$ . For example if  $(p, q) = (2, 3)$ , this would be the set  $\{\frac{3}{7}, \frac{6}{7}\}$ .

If instead  $r_2 = 0$ , then the condition becomes  $t \in \{0, 1\} \cap (0, 1) = \emptyset$ .

But we also need two more points,  $x_1, x_3$  such that  $0 < x_1 < x_2 < x_3 < 1$  and  $\tilde{\gamma}_{r,\theta}^{1,2}(x_1) = \tilde{\gamma}_{r,\theta}^{1,2}(x_3)$ .

When  $r_1 = 0$ , this amounts to

$$(x_3 - x_1)(q + 2p) \in q\mathbb{Z}, \quad \text{that is} \quad x_3 - x_1 \in \frac{q}{q+2p}\mathbb{Z}$$

If  $(p, q) = (2, 3)$  then  $\frac{q}{q+2p} = \frac{3}{7}$ , so  $x_3 - x_1 \in \frac{3}{7}\mathbb{Z}$ . Naturally, there are quite a lot of such intersection points.

We don't necessarily even need to change to  $\tilde{Z}_{l,m}$ . Suppose we choose the points  $x_1, x_2, x_3$ .

Since  $Z_{l,m}(r, \theta)$  is contained in a torus, our loops  $\Upsilon Z_{l,m}(r, \theta)$  will be  $Z_{l,m}[x_2, x_1] \star Z_{l,m}[x_3, x_2] \star Z_{l,m}[0, x_3] \star Z_{l,m}[x_1, 0]$ .

Now, let  $S^1 \times S^1/\mathbb{Z}/p$  denote the torus quotiented out by the action of  $\mathbb{Z}/p$  on it. Then we find that

$$\pi_1(S^1 \times S^1/\mathbb{Z}/p) \cong \langle a, b, c \mid ab^q = c^p \rangle^{ab}$$

So  $Z_{l,m}(r, \theta)$  corresponds to  $c^l b^m$ .

Now, in  $S^1 \times S^1/\mathbb{Z}/p$ , we can take a path from  $Z_{l,m}(r, \theta)(x_1) = Z_{l,m}(r, \theta)(x_3)$  to  $Z_{l,m}(r, \theta)(0)$  and we can homotope our loop  $Z_{l,m}(r, \theta)$  such that  $Z_{l,m}(r, \theta)(0) = Z_{l,m}(r, \theta)(x_i)$  for  $i = 1, 2, 3$ . See figure 5

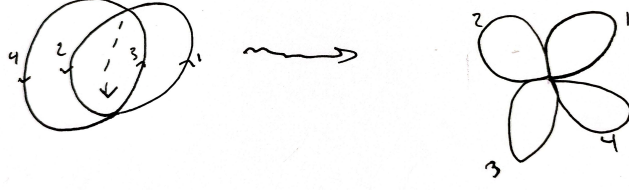


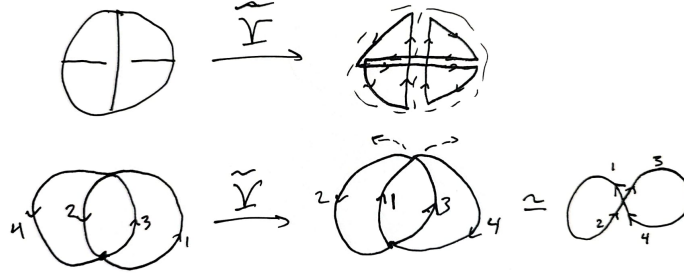
FIGURE 5.

But in this loop, each of the segments  $Z_{l,m}[x_i, x_j]$  is a loop of its own, hence lies in  $\pi_1(S^1 \times S^1/\mathbb{Z}/p)$  which is abelian, so in particular,

$$\begin{aligned} \wedge_{\Delta^3} Z_{l,m}(r, \theta) &= Z_{l,m}[x_2, x_1] \star Z_{l,m}[x_3, x_2] \star Z_{l,m}[0, x_3] \star Z_{l,m}[x_1, 0] \\ &\simeq Z_{l,m}[0, x_3] \star Z_{l,m}[x_3, x_2] \star Z_{l,m}[x_2, x_1] \star Z_{l,m}[x_1, 0] \\ &= \overline{Z_{l,m}(r, \theta)} \end{aligned}$$

where the bar denotes the inverse loop.

We could likewise define other operations. For example, consider the following operation, which we will denote by  $\tilde{\Upsilon}$ :

FIGURE 6.  $\tilde{\Upsilon}$ 

Using the same approach as before, this becomes  $\gamma \mapsto \gamma[x_2, 0] \star \gamma[x_2, 1]$ , i.e, first half up to  $x_2$  is  $\gamma$  reversed up to  $x_2$ , and the second part is  $\gamma$  normally.

I believe this doesn't change the loop - i.e.,  $\tilde{\Upsilon}(\gamma) = \gamma$ . Question mark???

**Question 5.14.** We have the following composition:

$$C_3(\mathcal{L}_{p,q}) \xrightarrow{Z_{l,m}} C_3(L\mathcal{L}_{p,q}) \times^{\Delta^3/\partial\Delta^3} C_6(L\mathcal{L}_{p,q} \times \Delta^3/\partial\Delta^3) \xrightarrow{Ro[\tau_{\Delta^3} \cap]} C_0(L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3),$$

and we are interested in what the image of this composition is.

By definition, it will be a finite sum of loops with marked points,  $(\gamma, (x_1, x_2, x_3))$ , in  $L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3$  with coefficients in  $\mathbb{Z}$ .

Let us consider what this composition is doing. For some chain  $\sigma$  in  $\mathcal{L}_{p,q}$ , we apply  $Z_{l,m}$  to give a chain in  $L\mathcal{L}_{p,q}$ . Then we take the cross product with the quotient 3-chain  $\Delta^3 \rightarrow \Delta^3/\partial\Delta^3$ , which gives a 6-chain in  $L\mathcal{L}_{p,q} \times \Delta^3/\partial\Delta^3$ . Then  $[\tau_{\Delta^3} \cap]$

subdivides this chain until simplices are either in  $U_2$  or its complement, but still remaining homologous to the original chain, and then we apply  $\tau_{\Delta^3}$ , which has support in  $U_2$ , essentially only leaves the chains contained in  $U_2$ . In  $U_2$ , we can apply  $R$ , and the resulting 0-chain is the image. But furthermore, if the subdivided chain is transverse to  $L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3$ , the by Corollary 3.16, capping with the Thom class will just give us the intersection of the chain with  $L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3$ . So the problem reduces to figuring out how to make  $Z_{l,m} \times \Delta^3/\partial\Delta^3$  traverse to  $L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3$ . But since we know that we must end in  $C_0$  of the latter, we know that we must reduce to finite intersections.

So let us start with the  $\tilde{Z}_{l,m}$  from [8].

Recall that its locus of self-intersection was

$$\Sigma_{\Delta} = (\lambda \times I_1) \cup (\lambda' \times I_2) \subset \mathcal{L}_{p,q} \times (0,1)$$

where  $I_1 = \{\frac{1}{l}, \dots, \frac{l-1}{l}\}$  and  $I_2 = \{\frac{1}{pl+pm}, \dots, \frac{ql+pm-1}{ql+pm}\}$ , and  $\lambda, \lambda'$  are the loops parametrizing the degenerate tori (circles) at the endpoints  $r_2 = 0$  and  $r_1 = 0$ , respectively.

Now suppose  $x_2$  is a point such that for  $\gamma = Z_{l,m}((1,0),\theta)$ ,  $\gamma(0) = \gamma(x_2)$ . That is,  $\left((1, \theta_1 + \frac{lx_2}{p}), 0\right) = ((1, \theta_1), 0)$ . By adding  $\frac{\theta p}{l}$  to  $x_2$ , we may assume that  $\gamma = \lambda$ , and suppose  $x_2 \in I_1$ .

For  $0 < x_1 < x_2 < x_3 < 1$ , if  $\lambda(x_1) = \lambda(x_3)$ , then  $x_3 - x_1 \in \frac{1}{l}\mathbb{Z}$ . If  $l > 1$ , there are infinitely many such pairs.

For this, we must essentially break the periodicity in the angle coordinate. One possibility could be to let  $\theta_1(t) = \theta_1 + \sin(\pi t)$ .

Then for some  $0 < x_1 < x_2 < x_3 < 1$  to satisfy the criterion, say for  $r_1 = 1$  and  $r_2 = 0$ , we need  $\theta_1 + \sin(\pi x_2) + \frac{lx_2}{p} = \theta_1(x_2) + \frac{lx_2}{p} = \theta_1(0) = \theta_1$ , so  $\sin(\pi x_2) = \frac{lx_2}{p}$  which only has one possible solution for each  $x_2 \in (0,1)$  and all  $l, m$ .

Let  $g(t) = \sin(\alpha(l, m)t) - t \sin(\alpha(l, m))$ . Consider the functions  $\tilde{\theta}_1(t) = \theta_1 + \frac{lt}{p} + g(t)$  and  $\tilde{\theta}_2(t) = \theta_2 + \frac{lt}{p} + g(t)$ , and define  $Z'_{l,m}(r, \theta) = \gamma = \left[t \mapsto \left(\tilde{r}_1(t), \tilde{\theta}_1(t)\right), \left(\tilde{r}_2(t), \tilde{\theta}_2(t)\right)\right]$ .

For  $Z'_{l,m}(r, \theta)$  to be in  $L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} \Delta^3/\partial\Delta^3$ , we would need for some  $0 < x_1 < x_2 < x_3 < 1$  that  $\gamma(x_1) = \gamma(x_3)$  and  $\gamma(0) = \gamma(x_2)$ . Just as before, we deduce that  $r_1 = 0$  or  $r_2 = 0$ . Next if  $\gamma(x_1) = \gamma(x_3)$ , we must have  $g(x_1) - g(x_3) = \frac{l}{p}(x_3 - x_1)$  or  $(\frac{lq}{p} + m)(x_3 - x_1)$ .

If we simply choose  $\alpha(l, m)$  to be small enough, we can guarantee that this never happens. Thus  $Z'_{l,m}$  does not intersect  $L\mathcal{L}_{p,q} \times_{\mathcal{L}_{p,q}} \Delta^3/\partial\Delta^3$ .

$$\begin{array}{ccccccc}
C_3(L\mathcal{L}_{p,q}) \otimes C_3(\Delta^3/\partial\Delta^3) & \xrightarrow{\times} & C_6(L\mathcal{L}_{p,q} \times \Delta^3/\partial\Delta^3) & \xrightarrow{[\tau_{\Delta^3} \cap]} & C_0(U_2) & \xrightarrow{R} & C_0(L\mathcal{L}_{p,q} \times_M \Delta^3/\partial\Delta^3) \\
\downarrow & & \downarrow E_* & & \downarrow E_* & & \downarrow r \circ ev_{old} \\
C_3(\mathcal{L}_{p,q}^2) \otimes C_3(\mathcal{L}_{p,q}^2) & \xrightarrow{\times} & C_6(\mathcal{L}_{p,q}^4) & \xrightarrow{[\tau_M \times M \cap]} & C_0(U_1) & \xrightarrow{r} & C_0(\mathcal{L}_{p,q}^2)
\end{array}$$

So now for an arbitrary  $\sigma \in C_3(\mathcal{L}_{p,q})$ , we have that the composite that we are interested in is the same as  $\bullet \text{ev}'(Z_{l,m} \circ \sigma \otimes \Delta^3/\partial\Delta^3)$

We can again look at  $\tilde{Z}_{l,m}$  instead.

Recall the intersection product as the following composition

$$\bullet_{Th}: \Delta_p(M) \otimes \Delta_q(M) \xrightarrow{\times} \Delta_{p+q}(M \times M) \xrightarrow{[\tau_M \cap]} \Delta_{p+q-n}(U_M) \xrightarrow{r_*} \Delta_{p+q-n}(M)$$

## 6. TERMINOLOGY

**Definition 6.1** (Neighborhood retract). If  $A \subset X$  and  $A$  has a neighborhood in  $X$  of which it is a retract, then  $A$  is called a *neighborhood retract* (in  $X$ ).

*Note.* Saying that  $A \hookrightarrow X$  is a cofibration is stronger than saying that  $A$  is a neighborhood retract.

**Definition 6.2** (Exponential Map). Let  $M$  be a smooth manifold and  $p \in M$ . One can define the notion of a straight line through the point  $p$ .

Let  $v \in T_p M$  be a tangent vector to the manifold at  $p$ . Then there is a unique geodesic  $\gamma_v: [0, 1] \rightarrow M$  satisfying  $\gamma_v(0) = p$  with initial tangent vector  $\gamma'_v(0) = v$ . The corresponding *exponential map* is defined by  $\exp_p(v) = \gamma_v(1)$ .

**Definition 6.3** (Injectivity Radius). The injectivity radius of a Riemannian manifold at a point  $p$  is the supremum of all radii for which the exponential map at  $p$  is a diffeomorphism onto its image.

## 7. LEMMAS

**Lemma 7.1.** Let  $\pi: W \rightarrow N$  be a covering map and  $M$  a connected space. Suppose  $f, g: M \rightarrow W$  are maps such that  $\pi \circ f = \pi \circ g$  and that  $f(x) = g(x)$  for some  $x \in M$ . Then  $f = g$ .

*Proof.* Show that the set

$$Z = \{z \in M \mid f(z) = g(z)\}$$

is closed and open. □

**Lemma 7.2.** Suppose  $A \subset Y$ , and  $f: X \rightarrow Y$  is transverse to  $A$ . Then we claim that  $f^*(N_A Y) \cong N_{f^{-1}A}(X)$ . That is, the pullback of the normal bundle of  $A$  in  $Y$  is the normal bundle of the preimage of  $A$  in  $X$ .

*Proof.* We have an induced map pointwise

$$\begin{array}{ccc} T_x X & \xrightarrow{df} & T_{f(x)} Y \\ \downarrow & & \downarrow \\ (N_{f^{-1}(A)} X)_x = T_x X / T_x f^{-1}(A) & \xrightarrow{\overline{df}} & T_{f(x)} Y / T_{f(x)} A = (N_A Y)_{f(x)} \end{array}$$

defining  $\overline{df}: N_{f^{-1}(A)} X \rightarrow N_A Y$ . We also have the bundle map  $\pi: N_{f^{-1}(A)} X \rightarrow X$ , thus inducing a map  $\varphi: N_{f^{-1}A} X \rightarrow f^* N_A Y$  by  $\varphi(x, [v]) = (x, \overline{df}[v])$ . Now,  $\overline{df}$  can be seen to be injective directly, and surjectivity of  $\overline{df}$  follows from surjectivity of  $df$  which follows directly from our assumption of transversality. □

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