

# Topological Manifolds

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**Abstract**

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# 1 Point Set Topology of Topological Manifolds

## 1.1 Triangulation of Manifolds

## 1.2 Covering Spaces of Manifolds

### Proposition 1.2.1

Any covering space of a manifold is also a manifold.

## 2 Orientability of a Topological Manifold

### 2.1 Classical Orientability

Recall the notion of orientation in finite dimensional vector bases. We say that two bases of a vector space have the same orientation if the change of basis matrix has determinant greater than 0. Since topological manifolds locally look like  $\mathbb{R}^n$  which is a finite-dimensional vector space, we expect that orientations can be generalized to manifolds. In particular, what we seek in a notion of orientability should be invariant under rotations and translations, and reflections should flip the orientation, should it depend on points of the space.

Let us start by redefining orientation on  $\mathbb{R}^n$ . We propose the following definition. Let  $x \in \mathbb{R}^n$ . Recall that

$$H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\}) \cong \mathbb{Z}$$

Then there are only two generators of  $H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\})$ . An orientation at  $x \in \mathbb{R}^n$  is then a choice of generator. In order to extend this local notion into a global one, notice that a choice of orientation for any point automatically determines the orientation of every other point. Indeed if  $y \in \mathbb{R}^n$  is another point, then there exists an open ball  $B$  containing both  $x$  and  $y$ . Then by excision,

$$H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\}) \cong H_n(\mathbb{R}^n, \mathbb{R}^n \setminus B) \cong H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{y\})$$

Hence if we have chosen a generator on the left, we would have chosen a corresponding orientation on the right. Moreover, this choice of orientation is consistent throughout all the points of  $\mathbb{R}^n$ . This suggests that the difference between orientable and not orientable is whether there is a consistent choice of orientation, but not a question of existence.

The key observation in defining orientation through homology is the following proposition, which shows that the local homology groups on a manifold are isomorphic to  $\mathbb{Z}$  on the top dimension.

#### Proposition 2.1.1

Let  $M$  be a  $k$ -dimensional topological manifold and  $x \in M$  a point. Then

$$H_n(M, M \setminus \{x\}) \cong H_n(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\}) \cong \begin{cases} \mathbb{Z} & \text{if } n = k \\ 0 & \text{if } n \neq k \end{cases}$$

*Proof.* Let  $x \in U$  be an open neighbourhood such that  $U \cong \mathbb{R}^k$ . Then by excision, we have that

$$H_n(M \setminus (M \setminus U), (M \setminus \{x\}) \setminus (M \setminus U)) \cong H_n(M, M \setminus \{x\})$$

This translates to  $H_n(U, U \setminus \{x\}) \cong H_n(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\})$ . By corollary 5.2.3 in Algebraic Topology 2, we are done. Alternatively, we have the following proof:

If  $k = 0$ , the results are clear. If  $k \geq 1$ , then the long exact sequence of the pair  $(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\})$  together with the fact that  $\mathbb{R}^k \setminus \{*\} \simeq S^{k-1}$  and  $\mathbb{R}^k \simeq *$  gives

$$H_n(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\}) = 0$$

for  $n > k$  and  $n < k$ . When  $n = k$ , we have an exact sequence

$$0 \longrightarrow H_k(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\}) \longrightarrow H_{k-1}(S^{k-1}) \longrightarrow H_{k-1}(\mathbb{R}^k)$$

when  $k > 1$  since  $H_{k-1}(\mathbb{R}^k) = 0$ . Thus  $H_k(\mathbb{R}^k, \mathbb{R}^k \setminus \{*\}) \cong \mathbb{Z}$ . If  $k = 1$ , then the last map  $H_0(S^0) \rightarrow H_0(\mathbb{R})$  is given by the matrix  $\begin{pmatrix} 1 & 1 \end{pmatrix} : \mathbb{Z}^2 \rightarrow \mathbb{Z}$  thus also giving isomorphism.  $\square$

**Definition 2.1.2: Local Orientation**

Let  $M$  be a  $k$ -dimensional topological manifold and let  $x \in M$ . A local orientation of  $M$  at  $x$  is a choice of generator of

$$H_k(M, M \setminus \{x\}) \cong \mathbb{Z}$$

One can think of local orientation as follows. Choose an open neighbourhood  $U$  of  $x$  that is homeomorphic to  $\mathbb{R}^2$ . Then the long exact sequence for relative homology gives an isomorphism

$$H_2(U, U \setminus \{x\}) \cong H_1(S^1)$$

since  $U \setminus \{x\}$  deformation retracts onto a small circle around  $x$ , we can choose a local orientation  $\omega_x$  for the circle which is the same as choosing in which direction to loop around the circle. It remains to patch them up into a global orientation. Of course, this does not necessarily work for every single manifold.

Let  $U$  be a chart on a topological manifold  $M$  and that  $B \subseteq M$  is such that on the chart  $U$ ,  $B$  is an open / closed ball  $B_r(z)$ . For convention, we give a name to subsets of these type.

**Definition 2.1.3: Open and Closed Ball in Manifolds**

Let  $M$  be a  $k$ -dimensional topological manifold and let  $(U, \varphi)$  be a chart of  $M$ . We say that  $B \subset U$  is an open / closed ball if  $\varphi(B) \subseteq \mathbb{R}^k$  is an open / closed ball of  $\mathbb{R}^k$ .

The point of the definition is that we have the following sequence of isomorphisms

$$\begin{aligned} H_k(M, M \setminus B) &\cong H_k(U, U \setminus B) && \text{(Excise } M \setminus U) \\ &\cong H_k(\mathbb{R}^k, \mathbb{R}^k \setminus B_r(x)) \end{aligned}$$

and then using the long exact sequence in relative homology, we obtain an isomorphism

$$H_k(\mathbb{R}^k, \mathbb{R}^k \setminus B_r(x)) \cong H_{k-1}(\mathbb{R}^k \setminus B_r(x))$$

in which the latter space deformation retracts onto the boundary  $\partial B_r(x) \cong S^{k-1}$ . Thus

$$H_k(\mathbb{R}^k, \mathbb{R}^k \setminus B_r(x)) \cong H_{k-1}(\partial B_r(x)) \cong \mathbb{Z}$$

is infinite cyclic. This means that we can think of the choice of a local orientation as a choice of orientation on  $\partial B_r(x)$ .

Notice that the inclusion  $(M, M \setminus B) \hookrightarrow (M, M \setminus \{y\})$  induces a map in homology:

$$H_k(M, M \setminus B) \xrightarrow{\cong} H_k(M, M \setminus \{y\})$$

It is an isomorphism since  $B$  is homeomorphic to a ball in  $\mathbb{R}^k$  which is contractible. This leads to the following definition.

**Definition 2.1.4: Consistent Local Orientations**

Let  $(\omega_y)_{y \in B}$  be a family of local orientations. We say that it is consistent if there is a generator  $\omega_B \in H_k(M, M \setminus B)$  such that  $\omega_B \mapsto \omega_y$  for each  $y \in B$  under the isomorphism

$$H_k(M, M \setminus B) \cong H_k(M, M \setminus \{y\})$$

With this, we can now formally define orientations in a manifold.

**Definition 2.1.5: Orientation of a Manifold**

Let  $M$  be a  $k$ -dimensional topological manifold. An orientation of  $M$  is a function

$$x \mapsto \omega_x \in H_k(M, M \setminus \{x\})$$

assigning every point to a local orientation such that for every  $x \in M$ , there exists an open ball  $x \in B$  such that  $(\omega_x)_{x \in B}$  a consistent local orientation.

Since  $H_k(M, M \setminus \{x\})$  is isomorphic to  $\mathbb{Z}$ , this means that there are only two possible choices of distinct orientation classes for each point  $x \in M$ .

**Lemma 2.1.6**

The  $k$ -sphere  $S^k$  is orientable for any  $k \in \mathbb{N}$ .

*Proof.* Choose a fundamental class in  $H_k(S^k)$ . It is clear that the long exact sequence in relative homology induces a map

$$H_k(S^k) \rightarrow H_k(S^k, S^k \setminus \{x\})$$

induces local orientation at each point  $x \in S^k$ . They are locally consistent since the map factors through  $H_k(S^k, S^k \setminus B)$  for any open ball  $B$  in  $S^k$ .  $\square$

**2.2 The Orientation Bundle**

In order to deduce orientability of a manifolds, we appeal to the theory of vector bundles.

**Definition 2.2.1: Orientation Bundle**

Let  $M$  be a topological manifold. Define the orientation bundle  $\widetilde{M}$  to be the set of pairs

$$\widetilde{M} = \left\{ (x, \omega_x) \mid x \in M, \omega_x \in H_k(M, M \setminus \{x\}) \right\}$$

together the projection map  $\pi : \widetilde{M} \rightarrow M$  defined by  $\pi(x, \omega_x) = x$ .

**Definition 2.2.2: Topology on the Orientation Bundle**

Let  $M$  be a topological manifold. Define the topology on the orientation bundle  $\widetilde{M}$  as follows. Let  $B$  be an open ball in  $M$ . Since there are exactly two distinct orientation classes on  $B$  we have that

$$\pi^{-1}(B) = B_+ \amalg B_-$$

where  $B_+$  and  $B_-$  are homeomorphic to  $B$ . Define the topology of  $\widetilde{M}$  to be generated by sets of the form  $B_+$  and  $B_-$ .

**Lemma 2.2.3**

For any topological manifold  $M$ ,  $\widetilde{M}$  is a manifold and is a 2-sheeted covering.

*Proof.* Let  $(x, \omega_x)$  and  $(y, \omega_y)$  in  $\widetilde{M}$  be distinct. If  $x = y$  then  $\omega_x = -\omega_y$ . We know that there are two distinct orientation classes so  $\pi^{-1}$  is a disjoint union consisting of those with positive orientation and those with negative. Since  $\omega_x$  and  $\omega_y$  are opposite, they lie in the disjoint union separately so that they are disjoint. If  $x \neq y$ , then since  $M$  is Hausdorff then we can

choose  $U_1$  and  $U_2$  disjoint neighbourhoods of  $x$  and  $y$  respectively. Then this means that  $\pi^{-1}(U_1)$  and  $\pi^{-1}(U_2)$  are disjoint. Thus we have shown that  $M$  is Hausdorff.

Now let  $(x, \omega_x) \in \tilde{M}$ . Then since  $M$  is manifold, there is an open ball  $B$  around  $x$  so that  $B$  is homeomorphic to  $\mathbb{R}^k$ .  $\pi^{-1}(B)$  is then a disjoint union of two copies of  $B$ , one such copy contains  $(x, \omega_x)$ . Then we have found a neighbourhood for  $(x, \omega_x)$  that is homeomorphic to  $\mathbb{R}^k$ . Thus we are done.

It is clear that it is a two sheeted covering because for any open set  $B \subseteq M$ ,  $\pi^{-1}(B) = B_+ \amalg B_-$ . □

#### Lemma 2.2.4

Let  $M$  be a topological manifold. Then the orientation bundle  $\tilde{M}$  is orientable.

*Proof.* To show orientability, it suffices to show that for every  $(x, \omega_x) \in \tilde{M}$ , there is a choice of orientation such that there exists an open set in  $\tilde{M}$  for which the choice of orientation is locally consistent. So let  $(x, \omega_x)$  be a point in  $\tilde{M}$ . Let  $B$  be a small open ball around  $x$  in  $M$ . Then  $\pi^{-1}(B)$  is by definition a disjoint union of two copies of  $B$ , each with a locally consistent orientation. In other words,  $\pi^{-1}(B) = A \amalg C$ . Without loss of generality, take  $(x, \omega_x) \in A$ . Now consider the following isomorphisms

$$H_k(\tilde{M}, \tilde{M} \setminus \{(x, \omega_x)\}) \cong H_k(A, A \setminus \{(x, \omega_x)\}) \cong H_k(B, B \setminus \{x\}) \cong H_k(M, M \setminus \{x\})$$

The first isomorphism is obtained by excising the piece  $\tilde{M} \setminus A$ . The second isomorphism is obtained by considering the homeomorphism  $\pi|_A$ . The third isomorphism theorem is obtained by excising the piece  $M \setminus B$  from the right.

Thus for any choice of orientation in  $H_k(M, M \setminus \{x\})$  we obtain a choice of orientation in  $H_k(\tilde{M}, \tilde{M} \setminus \{(x, \omega_x)\})$ .

By two more excisions, we obtain

$$\begin{array}{ccc} H_k(\tilde{M}, \tilde{M} \setminus A) & \xrightarrow{\cong} & H_k(\tilde{M}, \tilde{M} \setminus \{(x, \omega_x)\}) \\ & & \uparrow \cong \\ H_k(M, M \setminus B) & \xrightarrow{\cong} & H_k(M, M \setminus \{x\}) \end{array}$$

Since  $A$  is a locally consistent choice of orientations, there exists a generator  $\omega_B \in H_k(M, M \setminus B)$  such that  $\omega_B \mapsto \omega_x$  under the bottom map of the diagram. This  $\omega_x$  then gives  $\tilde{\omega}_x \in H_k(\tilde{M}, \tilde{M} \setminus \{(x, \omega_x)\})$ . Which under the isomorphism of the top arrow in the diagram we obtain a generator of  $H_k(\tilde{M}, \tilde{M} \setminus A)$ . Since each operation described is independent of the choice of  $x \in B$ , the generator we obtained for  $H_k(\tilde{M}, \tilde{M} \setminus A)$  is independent of the choice of  $(x, \omega)_x$ . Thus the consistent local orientation condition is satisfied so that  $\tilde{M}$  is orientable. □

#### Lemma 2.2.5

The deck transformation of the orientation bundle of manifold is orientation reversing.

*Proof.* Any non-trivial deck transformation must permute the fibers of the covering space non-trivially. In this case, any  $(x, \omega_x)$  can only be mapped to the other of the element of the fiber which is  $(x, -\omega_x)$ . □

**Lemma 2.2.6**

Giving an orientation of  $M$  is equivalent to giving a continuous map  $s : M \rightarrow \widetilde{M}$  such that  $s \circ \pi = \text{id}$  (section of the orientation bundle).

*Proof.* Let  $s : M \rightarrow \widetilde{M}$  be continuous and that  $s \circ \pi = \text{id}$ . Then  $s$  assigns a orientation  $\omega_x$  to each  $x \in M$ . The map is continuous if and only if for each open ball in  $M$  and  $\pi^{-1}(B) = B_+ \amalg B_-$ , the preimages  $s^{-1}(B_+)$  and  $s^{-1}(B_-)$  are both open in  $B$ . Since these two preimages are disjoint and jointly cover  $B$ , this condition is equivalent  $s(B) = B_+$  or  $s(B) = B_-$ . This precisely means that the local orientations are consistent.  $\square$

**Theorem 2.2.7**

Let  $M$  be a connected topological manifold. Then exactly one of the following holds:

- $\widetilde{M} \rightarrow M$  is a non-trivial 2-sheeted cover and  $M$  is non-orientable
- $\widetilde{M} \cong M \amalg M$  and  $M$  admits precisely two orientations

*Proof.* Assume that  $\pi : \widetilde{M} \rightarrow M$  is connected and  $\omega : M \rightarrow \widetilde{M}$  is a continuous section to  $\pi$ . Let  $x \in M$  and  $\pi^{-1}(x) = \{(x, \omega_x), (x, -\omega_x)\}$ . By assumption there is a path  $\gamma$  in  $\widetilde{M}$  from  $(x, \omega_x)$  to  $(x, -\omega_x)$ . Then  $\gamma$  and  $\omega \circ \pi \circ \gamma$  are two paths in  $\widetilde{M}$  lifting  $\pi \circ \gamma$  and starting at  $(x, \omega_x)$ . But the first path ends at  $(x, -\omega_x)$  and the second one ends at  $(x, \omega_x)$ . This is a contradiction to the uniqueness of lifting paths. Thus  $M$  is non-orientable.

If  $M$  is disconnected then  $\widetilde{M} \cong M \amalg M$  since  $\widetilde{M}$  is a covering space. Thus  $M$  admits two orientations.  $\square$

**Corollary 2.2.8**

Any simply connected manifold is orientable.

*Proof.* By Galois theory of covering spaces, any 2-sheeted cover of a simply connected space is disconnected.  $\square$

**Proposition 2.2.9**

Let  $M$  be a connected compact smooth manifold of dimension  $n$ . If  $M$  is orientable then  $H_n(M) \cong \mathbb{Z}$ . Otherwise  $H_n(M) = 0$ .

**Proposition 2.2.10**

Let  $k \geq 1$ . Then  $\mathbb{RP}^k$  is orientable if and only if  $k$  is odd.

*Proof.* The quotient map  $q : S^k \rightarrow \mathbb{RP}^k$  is the unique connected two-sheeted cover of  $\mathbb{RP}^k$  by Galois theory for covering spaces. The non-trivial deck transformation is given by the antipodal map which has degree  $(-1)^{k+1}$ . If  $k$  is odd then this degree is 1 so that the deck transformation is orientation preserving. Since deck transformations of the orientation bundle must be orientation reversing, we conclude that  $S^k \neq \widetilde{\mathbb{RP}^k}$ . This means that the orientation bundle of  $\mathbb{RP}^k$  is disconnected.

Now assume that  $k$  is even. By the lifting criterion, there exists a lift of  $q$  called  $\tilde{q}$  such that



$$\begin{array}{ccc}
 & & \widetilde{\mathbb{RP}^k} \\
 & \nearrow \tilde{q} & \downarrow p \\
 S^k & \xrightarrow{q} & \mathbb{RP}^k
 \end{array}$$

where  $p$  is the covering map. Then  $\tilde{q}$  must also be a covering space. Assume that  $q$  is not injective. This means that  $\tilde{q} \circ (-\text{id}) = \tilde{q}$  since  $-\text{id}$  is the only other deck transformation of  $S^k$  over  $\mathbb{RP}^k$ . This means that for any  $x \in S^k$ , we have that

$$H_k(S^k) \xrightarrow{\tilde{q}} H_k(\widetilde{\mathbb{RP}^k}) \longrightarrow H_k(\widetilde{\mathbb{RP}^k}, \widetilde{\mathbb{RP}^k} \setminus \{\tilde{q}(x)\})$$

where the second map is given by the long exact sequence in relative homology. Denoting this entire map by  $\alpha$ , we have that  $\alpha \circ (-\text{id})_* = \alpha$  since  $\tilde{q} \circ (-\text{id}) = \tilde{q}$ . But  $\alpha$  is a map from  $\mathbb{Z}$  to  $\mathbb{Z}$ . Since  $\alpha \circ (-\text{id})_* = \alpha$  this implies that  $\alpha = 0$ . But  $\alpha$  also factors as

$$H_k(S^k) \xrightarrow{\cong} H_k(S^k, S^k \setminus \{x\}) \xrightarrow{\tilde{q}} H_k(\widetilde{\mathbb{RP}^k}, \widetilde{\mathbb{RP}^k} \setminus \{\tilde{q}(x)\})$$

by the long exact sequence in relative homology and naturality. But the second map is also an isomorphism since covering spaces of manifolds induces an isomorphism in local homology groups.

Now  $S^k$  being compact and  $\mathbb{RP}^k$  being Hausdorff together with  $\tilde{q}$  being injective implies that  $\tilde{q}$  is a homeomorphism onto an open and closed subspace of  $\mathbb{RP}^k$ . Assume that  $\tilde{q}$  is not surjective, then we have that  $\widetilde{\mathbb{RP}^k} \cong S^k \amalg X$  for some other space  $X$ . But this is impossible thus  $q$  is surjective and  $\tilde{q}$  gives a homeomorphism between  $S^k$  and  $\widetilde{\mathbb{RP}^k}$ . Since  $S^k$  is connected,  $\mathbb{RP}^k$  is thus non orientable.  $\square$

One has to be careful that homotopy equivalence does not preserve orientability. For example, the Möbius strip is homotopy equivalent to  $S^1$  but the former is non-orientable while the latter is.

## 2.3 Orientability in Arbitrary Coefficient Ring

### Definition 2.3.1: R-Orientation

Let  $M$  be an  $n$ -dimensional topological manifold. Let  $R$  be a ring. An  $R$ -orientation of  $M$  is an assignment

$$x \in M \mapsto \mu_x \in H_n(M, M \setminus \{x\}; R)$$

where  $\mu_x$  is a unit of  $R$ , such that the following local consistency condition holds.

For any point  $x \in M$ , there exists an open ball  $B \subseteq M$  and a generator  $\mu_B \in H_n(M, M \setminus B)$  such that for any  $y \in B$ , under the canonical isomorphism

$$H_n(M, M \setminus B; R) \cong H_n(M, M \setminus \{y\}; R)$$

the generator  $\mu_B$  is sent to  $\mu_y$ .

### Theorem 2.3.2

Let  $M$  be a closed and connected  $n$ -dimensional manifold. Let  $R$  be a ring. Then the following are true.

- If  $M$  is  $R$ -orientable, then the map

$$H_n(M; R) \rightarrow H_n(M, M \setminus \{x\}; R) \cong R$$

is an isomorphism for all  $x \in M$ .

- If  $M$  is not  $R$ -orientable, then the map

$$H_n(M; R) \rightarrow H_n(M, M \setminus \{x\}; R) \cong R$$

is injective and has image  $\{r \in R \mid 2r = 0\}$  for all  $x \in M$

- $H_i(M; R) = 0$  for all  $i > n$ .

### Corollary 2.3.3

Let  $M$  be a topological manifold of dimension  $n$ . Then there is an isomorphism

$$H_n(M; \mathbb{Z}/2\mathbb{Z}) \cong \mathbb{Z}/2\mathbb{Z}$$

## 2.4 Fundamental Class

### Definition 2.4.1: Fundamental Class

Let  $M$  be a closed and connected manifold of dimension  $n$ . Let  $R$  be a ring. A fundamental class for  $M$  with coefficients in  $R$  is an element  $[c] \in H_n(M; R)$  such that under the isomorphism

$$H_n(M; R) \cong H_n(M, M \setminus \{x\}; R) \cong R$$

the element  $[c]$  is sent to a generator of  $H_n(M, M \setminus \{x\}; R)$  for any  $x \in M$ .

### Lemma 2.4.2

Let  $M$  be a closed and connected manifold of dimension  $n$ . Let  $R$  be a ring. Then  $M$  is  $R$ -orientable if and only if  $M$  has a fundamental class for  $M$  with coefficients in  $R$ .

## 2.5 Simplicial Orientability

We can deduce orientability of manifolds using a simplicial version of the definition.

### Definition 2.5.1: Local Simplicial Orientation

Let  $M$  be a triangulable topological manifold. A local simplicial orientation on an  $n$ -simplex  $[v_0, \dots, v_n]$  in  $M$  is an equivalence class of choice of ordering of vertices that are different by an even permutation.

### Definition 2.5.2: Simplicial Orientability

Let  $M$  be a triangulable topological manifold of dimension  $n$  with finitely many simplices. We say that  $M$  is simplicially orientable if there exists a linear combination

$$\sum_{\sigma_i \text{ an } n\text{-simplex}} k_i \sigma_i$$

of  $n$ -simplices such that under the isomorphism

$$H_n(M; \mathbb{Z}) \cong H_n(M, M \setminus \{x\}; \mathbb{Z}) \cong \mathbb{Z}$$

the element is sent to a generator in  $H_n(M, M \setminus \{x\}; \mathbb{Z})$  for all  $x \in M$ .

Let  $[\sum_{i=1}^m k_i \sigma_i]$  be an element of  $H_n(M; \mathbb{Z})$ . We defined the element to be the fundamental class of  $M$  if this element maps to the generator of  $H_n(M, M \setminus \{x\}; R)$  for each  $x \in M$ . This already guarantees that  $k_i = \pm 1$ . If we also require that the orientation is consistent, then we must require also require that  $\sum_{i=1}^m k_i \sigma_i$  is a cycle.

**Proposition 2.5.3**

Let  $M$  be a triangulable topological manifold of dimension  $n$  with finitely many simplices. Then  $M$  is simplicially orientable via the linear combination

$$\sum_{\sigma_i \text{ an } n\text{-simplex}} k_i \sigma_i$$

of  $n$ -simplices if and only if it is a cycle and that  $k_i = \pm 1$  is a choice of local simplicial orientation of  $M$ .

**Theorem 2.5.4**

Let  $M$  be a triangulable topological manifold of dimension  $n$  with finitely many simplices. Then  $M$  is orientable if and only if  $M$  is simplicially orientable.

### 3 Poincare Duality

#### 3.1 The Cap Product

##### Definition 3.1.1: The Cap Product

Let  $\sigma = [v_0, \dots, v_k] \in C_k(X)$  and  $\phi \in C^l(X)$  where  $k \geq l$  with coefficients in a ring  $R$ . Define the cap product to be

$$\sigma \frown \phi = \phi(\sigma|_{[v_0, \dots, v_l]})\sigma|_{[v_l, \dots, v_k]} \in C_{k-l}(X)$$

##### Lemma 3.1.2

The cap product  $\frown: C_k(X) \times C^l(X) \rightarrow C_{k-l}(X)$  with coefficients in a ring  $R$  induces a cap product in homology  $\frown: H_k(X) \times H^l(X, R) \rightarrow H_{k-l}(X)$  for  $k \geq l$ .

#### 3.2 Cohomology with Compact Support

#### 3.3 The Duality Theorem

##### Theorem 3.3.1: Poincare Duality

Let  $M$  be a compact and oriented topological  $n$ -manifold. Then the homomorphism

$$D: H^p(M) \rightarrow H_{n-p}(M)$$

is an isomorphism.

## 4 The Theory of Surfaces

### 4.1 Classification of Compact Surfaces

Recall that a compact surface is a connected topological manifold of dimension 2 that is compact.

#### Definition 4.1.1: Connected Sum

Let  $S_1$  and  $S_2$  be two compact surfaces. Let  $D_i \subseteq S_i$  be two small closed disks for  $i = 1, 2$ . Define the connected sum to be

$$S_1 \# S_2 = \frac{(S_1 \setminus D_1^\circ) \amalg (S_2 \setminus D_2^\circ)}{\partial D_1 \cong \partial D_2}$$

#### Lemma 4.1.2

The connected sum of two compact surfaces is again a compact surface.

#### Proposition 4.1.3

The connected sum is invariant under the choice of homeomorphism and the location of the small discs.

We encounter our first family of compact surfaces by repeatedly applying connected sums to a number of toruses.

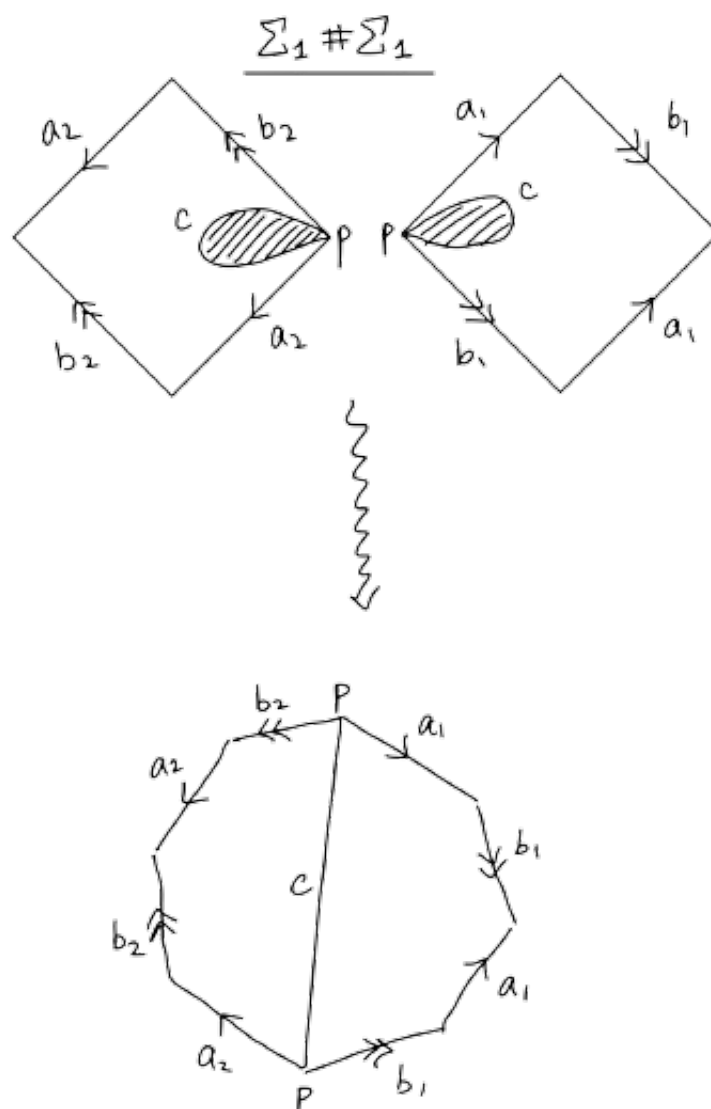
#### Definition 4.1.4: $g$ -Holed Torus

For  $g \geq 0$ , define the  $g$ -holed torus to be

$$\Sigma_g = \mathbb{T} \# \cdots \# \mathbb{T}$$

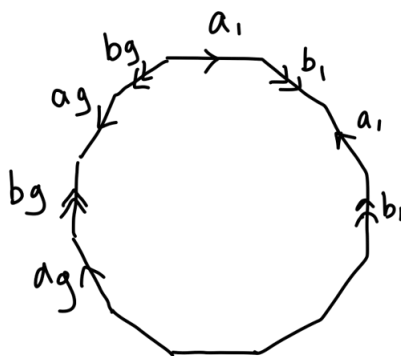
the connected sum of  $g$  toruses. By convention when  $g = 0$ ,  $\Sigma_g$  is the 2-sphere.

Recall the CW complex of the torus. We can visualize the connected sum of two toruses using the CW complex.



This is done by cutting a hole at the CW complex at the point  $p$ , and then pushing the boundary  $c$  out, and then connecting them together. The cut-out hole is exactly a disc in the torus. By gluing the two toruses along the boundary  $c$ , we are effectively gluing the two toruses along the discs.

The new heptagon obtained is precisely then the CW complex of  $\Sigma_2$ . In general, we can perform the operation of connected sum on a  $(4g - 4)$ -gon and a square. We then obtain the CW complex of the  $g$ -holed torus.



Another class of compact surfaces is the connected sum of projective spaces  $\mathbb{RP}^2$ .

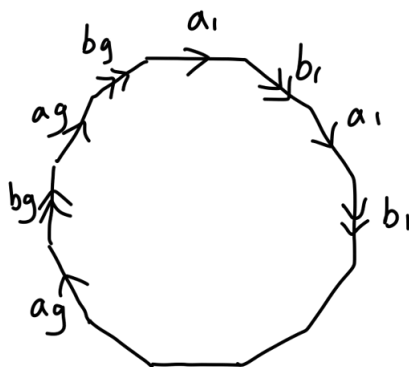
**Definition 4.1.5: Non-Orientable Surface**

For  $h \geq 1$ , define

$$N_h = \mathbb{RP}^2 \# \cdots \# \mathbb{RP}^2$$

the connected sum of  $h$  projective spaces.

We can do the same process of gluing the CW complexes just like that of the torus to obtain the  $4h$ -gon that represents  $N_h$ :



It is also meaningful to ask what would happen if we perform connected sums through the two class of compact surfaces. We obtain the following.

**Proposition 4.1.6**

Let  $N_3$  denote the connected sum of three projective spaces  $\mathbb{RP}^2$ . Then we have that

$$T \# \mathbb{RP}^2 = N_3$$

The above two classes of compact surfaces together with the sphere exhausts all possible cases for compact surfaces.

**Theorem 4.1.7**

Every compact surface is homeomorphic to exactly one of the following.

- $\Sigma_g$  for  $g \geq 0$
- $N_h$  for  $h \geq 1$

## 4.2 The (Co)Homology of Surfaces

Recall that a compact surface is a connected topological manifold of dimension 2 that is compact. Moreover, every compact surface is homeomorphic to either  $\Sigma_g = \mathbb{T} \# \cdots \# \mathbb{T}$  for  $g \geq 0$  or  $N_h = \mathbb{RP}^2 \# \cdots \# \mathbb{RP}^2$

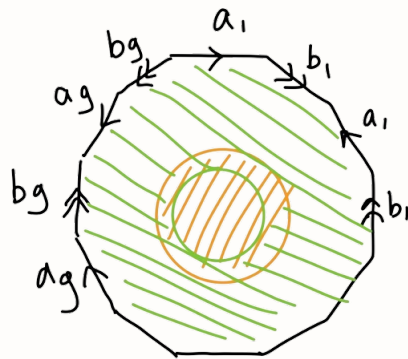
for  $h \geq 1$ . We can now compute the homology groups of these surfaces and moreover, show that  $\Sigma_g$  is orientable while  $N_h$  is not, using the CW complexes given above.

### Theorem 4.2.1

Let  $g \geq 0$ . The homology of the  $g$ -holed torus  $\Sigma_g$  is given by

$$H_n(\Sigma_g) = \begin{cases} \mathbb{Z} & \text{if } n = 0, 2 \\ \mathbb{Z}^{2g} & \text{if } n = 1 \\ 0 & \text{otherwise} \end{cases}$$

*Proof.* Cut an open disc along the middle of the CW complex as follows



and label it  $V$  (the orange part). Label the green part as  $U$ . It is clear that  $U \cap V \simeq S^1$ ,  $U$  is contractible and  $V$  deformation retracts to the boundary, which is actually just a wedge sum of  $2g$  circles. By the formula for the homology of wedge sums we have that

$$H_n(V) = \begin{cases} \mathbb{Z} & \text{if } n = 0 \\ \mathbb{Z}^{2g} & \text{if } n = 1 \\ 0 & \text{otherwise} \end{cases}$$

By the reduced Mayer-Vietoris sequence, the only non-trivial homology groups in the sequence are

$$0 \longrightarrow \tilde{H}_2(\Sigma_g) \longrightarrow \mathbb{Z} \longrightarrow \mathbb{Z}^{2g} \longrightarrow \tilde{H}_1(\Sigma_g) \longrightarrow 0$$

and the exact sequence

$$0 \longrightarrow \tilde{H}_0(\Sigma_g) \longrightarrow 0$$

in which the latter immediately shows that  $H_0(\Sigma_g) \cong \mathbb{Z}$ . Now the map  $\mathbb{Z} \rightarrow \mathbb{Z}^{2g}$  sends a generator of the first homology of  $U \cap V \simeq S^1$  to the loop

$$a_1 + b_1 - a_1 - b_1 + \cdots + a_g + b_g - a_g - b_g$$

Since  $\mathbb{Z}^{2g}$  is abelian, we conclude that this map is actually the zero map. It follows that  $H_2(\Sigma_g) \cong \mathbb{Z}$  and  $H_1(\Sigma_g) \cong \mathbb{Z}^{2g}$ .  $\square$

We can immediately deduce the orientability of  $\Sigma_g$  using the machinery in section 1.



## Corollary 4.2.2

The surfaces  $\Sigma_g$  for  $g \geq 0$  is orientable.

*Proof.* By the above, we have that  $H_2(\Sigma_g) \cong \mathbb{Z}$ . The long exact sequence for relative homology groups give

$$\cdots \longrightarrow H_2(\Sigma_g \setminus \{x\}) \longrightarrow H_2(\Sigma_g) \longrightarrow H_2(\Sigma_g, \Sigma_g \setminus \{x\}) \longrightarrow H_1(\Sigma_g \setminus \{x\}) \longrightarrow H_1(\Sigma_g) \longrightarrow \cdots$$

Let  $U$  be as the proof above. Then the inclusion from  $U$  to  $\Sigma \setminus \{x\}$  is a homotopy equivalence. Moreover,  $\Sigma \setminus \{x\}$  is a  $2g$ -fold wedge of circles labelled  $a_1, b_1, \dots, a_g, b_g$  and  $H_2(\Sigma_g \setminus \{x\}) = 0$ . Also, we have that  $H_1(U) \cong H_1(\Sigma_g)$  from above and hence  $H_1(\Sigma_g \setminus \{x\}) \cong H_1(\Sigma_g)$ . The last map is invertible so that by exactness, the third map is the zero map. Then what remains is an isomorphism

$$H_2(\Sigma_g) \cong H_2(\Sigma_g, \Sigma_g \setminus \{x\})$$

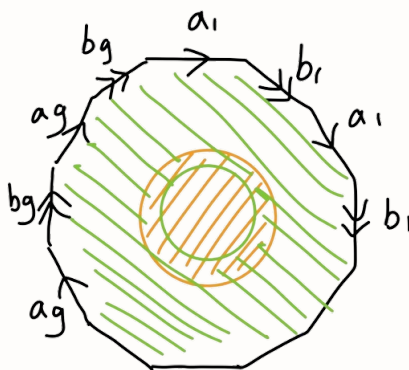
Now since this isomorphism factors through  $H_2(\Sigma_g, \Sigma_g \setminus B)$  for any ball  $B$  containing  $x$ , we thus have a consistent local orientation throughout all of  $\Sigma_g$ .  $\square$

## Theorem 4.2.3

Let  $h \geq 1$ . The homology of  $N_h$  is given by

$$H_n(N_h) = \begin{cases} \mathbb{Z} & \text{if } n = 0 \\ \mathbb{Z}^{h-1} \oplus \mathbb{Z}/2\mathbb{Z} & \text{if } n = 1 \\ 0 & \text{otherwise} \end{cases}$$

*Proof.* Similar to the proof in that of  $\Sigma_g$ , cut an open disc along the middle of the CW complex of  $N_h$  as follows



and again label the green part  $U$  and the orange part  $V$ . Then apply Mayer-Vietoris sequence to acquire a similar exact sequence

$$0 \longrightarrow \tilde{H}_2(\Sigma_g) \longrightarrow \mathbb{Z} \longrightarrow \mathbb{Z}^h \longrightarrow \tilde{H}_1(\Sigma_g) \longrightarrow 0$$

together with  $\tilde{H}_0(N_h) \cong 0$ . Notice that the third non-zero term counting from the left is now  $\mathbb{Z}^h$  instead of  $\mathbb{Z}^{2g}$  as in the torus because the boundary circle is the wedge sum of  $h$  circles labelled  $a_1 b_1, \dots, a_h b_h$ . The map  $\mathbb{Z}$  to  $\mathbb{Z}^h$  is now given by sending the generator 1 to

$$2(a_1 + b_1 + \cdots + a_h + b_h)$$

The Smith Normal form of the matrix is an  $h \times 1$  matrix with 2 at the first entry and 0 everywhere else. In particular, it means that this map is injective so that  $\tilde{H}_2(N_h) \rightarrow \mathbb{Z}$  is the 0 map so that  $\tilde{H}_2(N_h) \cong 0$ . Now it remains an exact sequence

$$0 \longrightarrow \mathbb{Z} \longrightarrow \mathbb{Z}^h \longrightarrow \tilde{H}_1(N_h) \longrightarrow 0$$

The image of the matrix is  $2\mathbb{Z}$  and by exactness this is the kernel of the map  $\mathbb{Z}^h \rightarrow \tilde{H}_1(N_h)$ . Thus we have an isomorphism

$$\tilde{H}_1(N_h) \cong \mathbb{Z}^{h-1} \oplus \mathbb{Z}/2\mathbb{Z}$$

and so we conclude.  $\square$

#### Corollary 4.2.4

The surfaces  $N_h$  for  $h \geq 1$  is non-orientable.

*Proof.* Notice that removing a small closed disk from  $\mathbb{RP}^2$  yields a space homeomorphic to the open Mobius strip. It follows that for  $h > 0$ , the space  $N_h$  contains the open Mobius strip as a subspace. Since the Mobius strip is non-orientable,  $N_h$  is also non-orientable.  $\square$

#### Theorem 4.2.5

Let  $g \geq 0$ . The singular cohomology of the  $g$ -holed torus  $\Sigma_g$  with coefficients in  $\mathbb{Z}$  is given by

$$H^n(\Sigma_g; \mathbb{Z}) = \begin{cases} \mathbb{Z} & \text{if } n = 0, 2 \\ \mathbb{Z}^{2g} & \text{if } n = 1 \\ 0 & \text{otherwise} \end{cases}$$

*Proof.* We use the universal coefficient theorem in all dimensions. When  $n = 0$ , we have that

$$\begin{aligned} H^0(\Sigma_g; \mathbb{Z}) &\cong \text{Hom}(H_0(\Sigma_g; \mathbb{Z}), \mathbb{Z}) \oplus \text{Ext}(H_{-1}(\Sigma_g; \mathbb{Z}), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}, \mathbb{Z}) \oplus 0 \\ &\cong \mathbb{Z} \end{aligned}$$

When  $n = 1$ , we have that

$$\begin{aligned} H^1(\Sigma_g; \mathbb{Z}) &\cong \text{Hom}(H_1(\Sigma_g), \mathbb{Z}) \oplus \text{Ext}(H_0(\Sigma_g), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}^{2g}, \mathbb{Z}) \oplus \text{Ext}(\mathbb{Z}, \mathbb{Z}) \\ &\cong \mathbb{Z}^{2g} \oplus 0 \\ &\cong \mathbb{Z}^{2g} \end{aligned}$$

When  $n = 2$ , we have that

$$\begin{aligned} H^2(\Sigma_g; \mathbb{Z}) &\cong \text{Hom}(H_2(\Sigma_g), \mathbb{Z}) \oplus \text{Ext}(H_1(\Sigma_g), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}, \mathbb{Z}) \oplus \text{Ext}(\mathbb{Z}^{2g}, \mathbb{Z}) \\ &\cong \mathbb{Z} \oplus 0 \\ &\cong \mathbb{Z} \end{aligned}$$

When  $n \geq 3$ , we have that

$$\begin{aligned} H^n(\Sigma_g; \mathbb{Z}) &\cong \text{Hom}(H_n(\Sigma_g), \mathbb{Z}) \oplus \text{Ext}(H_{n-1}(\Sigma_g), \mathbb{Z}) \\ &\cong \text{Hom}(0, \mathbb{Z}) \oplus \text{Ext}(H_{n-1}(\Sigma_g), \mathbb{Z}) \end{aligned}$$

When  $n \geq 4$ , then  $H_{n-1}(\Sigma_g) = 0$  hence the cohomology group is 0. When  $n = 3$ ,  $H_2(\Sigma_g) \cong \mathbb{Z}$  is a free abelian group hence the cohomology group is 0.  $\square$

We use the cohomology of  $\Sigma_g$  to illustrate generators of cohomology. Ref: Hatcher Ex3.7.

#### Theorem 4.2.6

Let  $h \geq 1$ . The singular cohomology of non-orientable surface  $N_h$  with coefficients in  $\mathbb{Z}$  is given by

$$H^n(N_h; \mathbb{Z}) = \begin{cases} \mathbb{Z} & \text{if } n = 0 \\ \mathbb{Z}^{h-1} & \text{if } n = 1 \\ \mathbb{Z}/2\mathbb{Z} & \text{if } n = 2 \\ 0 & \text{otherwise} \end{cases}$$

*Proof.* We use the universal coefficient theorem in all dimensions. When  $n = 0$ , we have that

$$\begin{aligned} H^0(N_h; \mathbb{Z}) &\cong \text{Hom}(H_0(N_h; \mathbb{Z}), \mathbb{Z}) \oplus \text{Ext}(H_{-1}(N_h; \mathbb{Z}), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}, \mathbb{Z}) \oplus 0 \\ &\cong \mathbb{Z} \end{aligned}$$

When  $n = 1$ , we have that

$$\begin{aligned} H^1(N_h; \mathbb{Z}) &\cong \text{Hom}(H_1(N_h; \mathbb{Z}), \mathbb{Z}) \oplus \text{Ext}(H_0(N_h; \mathbb{Z}), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}^{h-1} \oplus \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}) \oplus \text{Ext}(\mathbb{Z}, \mathbb{Z}) \\ &\cong \mathbb{Z}^{h-1} \oplus 0 \\ &\cong \mathbb{Z}^{h-1} \end{aligned}$$

When  $n = 2$ , we have that

$$\begin{aligned} H^2(N_h; \mathbb{Z}) &\cong \text{Hom}(H_2(N_h; \mathbb{Z}), \mathbb{Z}) \oplus \text{Ext}(H_1(N_h; \mathbb{Z}), \mathbb{Z}) \\ &\cong \text{Hom}(\mathbb{Z}, \mathbb{Z}) \oplus \text{Ext}(\mathbb{Z}^{h-1} \oplus \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}) \\ &\cong 0 \oplus \text{Ext}(\mathbb{Z}^{h-1}, \mathbb{Z}) \oplus \text{Ext}(\mathbb{Z}/2\mathbb{Z}, \mathbb{Z}) \\ &\cong 0 \oplus 0 \oplus \mathbb{Z}/2\mathbb{Z} \\ &\cong \mathbb{Z}/2\mathbb{Z} \end{aligned}$$

When  $n \geq 3$ , we have that

$$\begin{aligned} H^n(N_h; \mathbb{Z}) &\cong \text{Hom}(H_n(N_h; \mathbb{Z}), \mathbb{Z}) \oplus \text{Ext}(H_{n-1}(N_h; \mathbb{Z}), \mathbb{Z}) \\ &\cong \text{Hom}(0, \mathbb{Z}) \oplus \text{Ext}(0, \mathbb{Z}) \\ &\cong 0 \end{aligned}$$

and so we conclude. □

### 4.3 The Euler Characteristic

Recall that if  $X$  is a CW complex such that  $U \cap V = X$  and  $U$  and  $V$  are open subsets, then we have the formula

$$\chi(X) = \chi(U) + \chi(V) - \chi(U \cap V)$$

#### Corollary 4.3.1

Let  $S_1 \# S_2$  be the connected sum of two compact surfaces, then we have that

$$\chi(S_1 \# S_2) = \chi(S_1) + \chi(S_2) - 2$$

*Proof.* Let  $D_i$  be the gluing discs for  $S_i$  for  $i = 1, 2$ . Using the above formula, we have that

$$\chi(S_i) = \chi(D_i) + \chi(S_i \setminus D_i^\circ) - \chi(S^1)$$

since the intersection of the disc and  $S_i$  is  $S^1$ . It follows that

$$\begin{aligned} \chi(S_1 \# S_2) &= \chi(S_1 \setminus D_1^\circ) + \chi(S_2 \setminus D_2^\circ) - \chi(S^1) \\ &= \chi(S_1) + \chi(S_2) - 2 \end{aligned}$$

and so we conclude.  $\square$

### Corollary 4.3.2

For  $g \geq 0$  and  $h > 1$ , the Euler characteristic of any compact surface is given by

$$\chi(\Sigma_g) = 2 - 2g \quad \text{and} \quad \chi(N_h) = 2 - h$$

*Proof.* It follows directly by repeated applications of the above corollary.  $\square$

Recall that if  $p : \tilde{X} \rightarrow X$  is a  $d$ -sheeted covering and  $X$  is a finite CW complex, then we have the formula

$$\chi(\tilde{X}) = d \cdot \chi(X)$$