

Persistent Homology and TDA

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Chapter 1

Chain Complexes And Simplicial Homology

1.1 Introduction

The key method of algebraic topology is to assign various *algebraic structures* – groups, rings, modules – to topological spaces. This should be done in a *functorial way*. Roughly, functoriality means that maps of topological spaces (and compositions thereof) give rise to homomorphisms of the respective algebraic structures (and compositions thereof), and that the structures assigned to homeomorphic spaces are isomorphic. See (2.1) or [Hat02][Ch.2.3] for a more detailed discussion. In this way, we can think of these algebraic structures as *invariants* of the spaces under consideration. Questions about topological spaces are converted into questions about algebraic structures, which are typically “more rigid”. This rigidity can be used to demonstrate, for example, that maps between certain spaces do not exist, or that certain spaces are not homeomorphic, etc.

Computing these algebraic invariants is a different matter altogether. There are notorious examples of invariants that are unknown or hard to compute even for simple enough spaces, such as spheres.

1.2 Δ -complexes

We begin now with a setup that allows for fairly easy calculations. We shall assign a collection of abelian groups to a topological space X *equipped with some additional structure*. This additional structure – called Δ -*complex structure* – is a way of “parametrizing” X by points, segments, triangles, tetrahedra (and their higher-dimensional analogues) and will be introduced in Definition 1.2.2. While the structure of a Δ -complex makes computations easy, it will be completely unclear whether the groups that we obtain are sensitive to this additional structure, or are in fact invariants of the space X itself. In other words, the functoriality of this construction will be completely unclear. This will be rectified in Chapter 2.

We start with the basic building blocks: simplices.

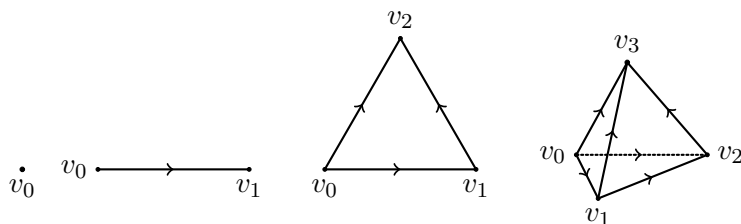
Definition 1.2.1 (Standard Simplex). *The standard n -simplex in \mathbb{R}^{n+1} is the convex hull Δ^n of the standard basis vectors $\{e_0, \dots, e_n\}$, i.e.,*

$$\Delta^n = \left\{ (t_0, t_1, \dots, t_n) \in \mathbb{R}^{n+1} \left| \sum_{i=0}^n t_i = 1, \ t_i \geq 0 \ \forall i \right. \right\} \subseteq \mathbb{R}^{n+1}.$$

More generally, an n -simplex in \mathbb{R}^{n+1} is the convex hull $[v_0, \dots, v_n]$ of any $(n+1)$ -tuple of vectors $v_0, \dots, v_n \in \mathbb{R}^{n+1}$ that do not lie in an n -dimensional hyperplane.

Notice that with this definition, $\Delta^n = [e_0, \dots, e_n]$.

Thus an n -simplex (plural simplices) is an n -dimensional analog of a triangle. A 0 -simplex is a point, a 1 -simplex is a line segment, a 2 -simplex is a triangle, 3 -simplex is a tetrahedron, as shown below.



The vectors v_i , determining $[v_0, \dots, v_n]$ are the *vertices* of the simplex. In our calculations we are going to work with a chosen *ordering* of the vertices of the simplex. I.e., we are going to use “simplex” when we mean “a simplex together with an ordering of the vertices”. This has a number of consequences. First, it determines orientations of the edges $[v_i, v_j]$ according to increasing subscripts. Second, specifying an ordering of the vertices determines a canonical linear homeomorphism from Δ^n onto any n -simplex $[v_0, \dots, v_n]$ preserving the order of vertices, namely, $\sum_i t_i \mathbf{e}_i \mapsto \sum_i t_i \mathbf{v}_i$. Once we fix an ordering of the vertices, we also obtain an orientation of the n -simplex, i.e., the sign of $\det(v_0, \dots, v_n)$. Two orderings determine the same orientation when they differ by an even permutation.

By a *face* of a n -simplex we shall mean an $(n - 1)$ -simplex spanned by some n -tuple of vertices of the simplex. That is, the i -th face of $[v_0, \dots, v_n]$ is $[v_0, \dots, \widehat{v}_i, \dots, v_n]$, where the hat indicates omission. Some sources refer to this face as an $(n - 1)$ -face, and introduce, more generally k -faces, for $0 \leq k \leq n - 1$. These are k -simplices, obtained as the convex hull of a k -tuple of vertices. We always order the vertices of a face according to their order in the larger simplex.

Example 1.2.1. Consider the (second) face $[v_0, v_1, v_3]$ of the 3-simplex $[v_0, v_1, v_2, v_3]$ in \mathbb{R}^4 . The canonical order-preserving map $\Delta^2 \rightarrow [v_0, v_1, v_3]$ is determined by $e_0 \mapsto v_0$, $e_1 \mapsto v_1$, $e_2 \mapsto v_3$. The canonical order-preserving map from Δ^1 to the edge $[v_1, v_3]$ is determined by $e_0 \mapsto v_1$, $e_1 \mapsto v_3$.

The *boundary* $\partial\Delta^n$ of the standard simplex is defined as the union of all the faces of Δ^n , and $\mathring{\Delta}^n = \Delta^n - \partial\Delta^n$ denotes interior of Δ^n . We define analogously the boundary and interior of an arbitrary simplex in \mathbb{R}^n . Notice that with this definition $\partial\Delta^0 = \emptyset$ and $\mathring{\Delta}^0 = \Delta^0$!

We now equip X with additional structure: “parametrization” of X by simplices of various dimensions that satisfies a number of compatibility conditions.

Definition 1.2.2 (Δ -complex). A Δ -complex structure on a topological space X is a collection of maps $\{\sigma_\alpha : \Delta^n \rightarrow X\}_\alpha$, with $n = n(\alpha)$ depending on the index α , such that:

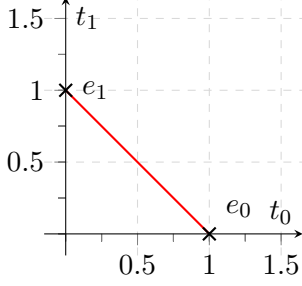
1. Each restriction $\sigma_\alpha|_{\mathring{\Delta}^n}$ is injective, and each point of X is in the image of exactly one such restriction $\sigma_\alpha|_{\mathring{\Delta}^n}$.
2. Each restriction of σ_α to a face of Δ^n is one of the maps $\sigma_\beta : \Delta^{n-1} \rightarrow X$. Here a face of Δ^n is identified with Δ^{n-1} via the canonical order-preserving linear homeomorphism.
3. A set $A \subset X$ is open iff $\sigma_\alpha^{-1}(A)$ is open in Δ^n for each σ_α .

Example 1.2.2. Consider $X = S^1 = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 = 1\}$. We are going to describe explicitly two maps $\sigma_0 : \Delta^0 \rightarrow S^1$, $\sigma_1 : \Delta^1 \rightarrow S^1$, which equip S^1 with the structure of a Δ -complex.

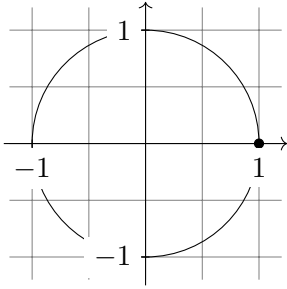
For the explicit description, keep in mind that $\Delta^0 = \{1\} \subseteq \mathbb{R}$ and that

$$\Delta^1 = \{(t_0, t_1) \mid t_0 + t_1 = 1\} = \{(t_0, 1 - t_0), t_0 \in [0, 1]\}$$

So in particular, any (continuous) map $\Delta^1 \rightarrow S^1$ is determined by and determines a (continuous) map $[0; 1] \rightarrow S^1$.



First, we define $\sigma_0 : \Delta^0 \rightarrow S^1$ by $\sigma_0(1) = (1, 0)$. Next, $\sigma_1 : \Delta^1 \rightarrow S^1$ is defined by $\sigma_1(t_0, t_1) = (\cos(2\pi t_0), \sin(2\pi t_0))$, which is clearly continuous. The map σ_1 is one-to-one on $\mathring{\Delta}^1$, and so is, trivially, σ_0 on $\mathring{\Delta}^0$. The images of the two maps cover the circle, with $\sigma_1(\mathring{\Delta}^1) = S^1 \setminus \{(1, 0)\}$ and $\sigma_0(\mathring{\Delta}^0) = \{(1, 0)\}$.



Finally, we check the compatibility property (2) of σ_1 and σ_0 . The restrictions of σ_1 to the two faces of Δ^1 coincide with σ_0 :

$$\begin{aligned}\sigma_1|_{[e_1]} &= \sigma_1(0, 1) = (\cos(0), \sin(0)) = (1, 0) = \sigma_0(1) \\ \sigma_1|_{[e_0]} &= \sigma_1(1, 0) = (\cos(2\pi), \sin(2\pi)) = (1, 0) = \sigma_0(1)\end{aligned}$$

Property (3) holds as well. There are numerous other Δ -complex structures on S^1 , and we shall discuss some of them later on.

Example 1.2.3. Our next example is a Δ -complex structure on $X = S^2 = \{(x, y, z) \in \mathbb{R}^3 \mid x^2 + y^2 + z^2 = 1\}$.

Notice first that there is a homeomorphism between the L^1 -sphere

$$\{(x_0, x_1, x_2) \mid |x_0| + |x_1| + |x_2| = 1\} \subseteq \mathbb{R}^3$$

and S^2 , given by

$$(x_0, x_1, x_2) \mapsto \left(\frac{x_0}{\sqrt{x_0^2 + x_1^2 + x_2^2}}, \frac{x_1}{\sqrt{x_0^2 + x_1^2 + x_2^2}}, \frac{x_2}{\sqrt{x_0^2 + x_1^2 + x_2^2}} \right),$$

that is, by $\mathbf{x} \mapsto \frac{\mathbf{x}}{\|\mathbf{x}\|}$.

On the other hand, the L^1 -sphere is the union of eight 2-simplices: one of them is the standard simplex Δ^2 in \mathbb{R}^3 , while the others are obtained from Δ^2 by reflection with respect to a coordinate plane, i.e., by multiplying one of the variables by ± 1 . Composing with the map between the L^1 and L^2 sphere, we obtain the eight continuous maps

$$\sigma_{s_0 s_1 s_2} : \Delta^2 = [e_0, e_1, e_2] \longrightarrow S^2,$$

$s_i \in \{\pm 1\}$, $i \in \{0, 1, 2\}$,

$$\sigma_{s_0 s_1 s_2} : (t_0, t_1, t_2) \mapsto (s_0 t_0, s_1 t_1, s_2 t_2) \mapsto \frac{(s_0 t_0, s_1 t_1, s_2 t_2)}{\sqrt{t_0^2 + t_1^2 + t_2^2}}.$$

Next, we have the three standard order-preserving homeomorphisms, identifying Δ^1 with the three faces (edges) of Δ^1 , $[e_1, e_2]$, $[e_0, e_2]$, $[e_0, e_1]$. Each of these edges is contained in a coordinate plane in \mathbb{R}^3 , and performing a reflection with respect to the coordinate planes orthogonal to the plane containing the edge gives rise to 12 maps from Δ^1 to the sphere.

Explicitly, these are the 12 continuous maps

$$\lambda_{0s_0s_1}, \lambda_{s_00s_1}, \lambda_{s_0s_10} : \Delta^1 \longrightarrow S^2,$$

where $s_i \in \{\pm 1\}$ and

$$\begin{aligned} \lambda_{0s_0s_1} : (t_0, t_1) &\longmapsto (0, s_0t_0, s_1t_1) \longmapsto \frac{(0, s_0t_0, s_1t_1)}{\sqrt{t_0^2 + t_1^2}} \\ \lambda_{s_00s_1} : (t_0, t_1) &\longmapsto (s_0t_0, 0, s_1t_1) \longmapsto \frac{(s_0t_0, 0, s_1t_1)}{\sqrt{t_0^2 + t_1^2}} \\ \lambda_{s_0s_10} : (t_0, t_1) &\longmapsto (s_0t_0, s_1t_1, 0) \longmapsto \frac{(s_0t_0, s_1t_1, 0)}{\sqrt{t_0^2 + t_1^2}}. \end{aligned}$$

Finally, we have six maps $\Delta^0 \rightarrow S^2$, obtained by composing the three inclusions of Δ^0 as a 0-face in Δ^2 , composed with reflections with respect to the coordinate planes. Explicitly, these are the 6 maps

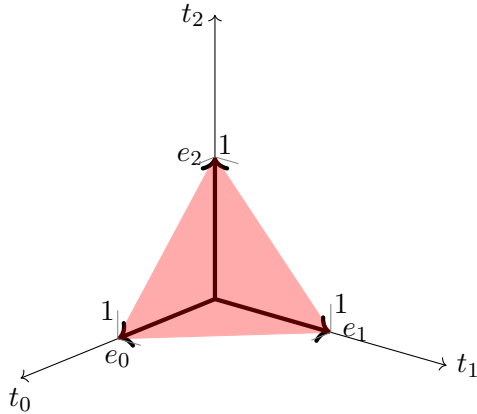
$$\mu_{s00}, \mu_{0s0}, \mu_{00s} : \Delta^1 \longrightarrow S^2,$$

where $s \in \{\pm 1\}$ and

$$\mu_{s00}(1) = (s, 0, 0), \mu_{0s0}(1) = (0, s, 0), \mu_{00s}(1) = (0, 0, s).$$

The images of the maps cover S^2 , they are injective when restricted to the interiors of the simplices and are compatible. For example, $\sigma_{s_0s_1s_2}|_{[e_1, e_2]} = \lambda_{0s_1s_2}$, $\lambda_{s_0s_10}|_{[e_0]} = \mu_{s_000}$, etc. suppressing the canonical orientation-preserving homeomorphism between simplices. Moreover, property (3) is satisfied. We do not check it explicitly, but it follows from the fact that our maps are obtained as composition of inclusion of a face into a simplex, followed by a reflection and a homeomorphism between the L^1 and L^2 sphere.

Altogether, this Δ -complex structure on S^2 consists of the eight maps $\sigma_{s_0s_1s_2}$, the twelve maps $\lambda_{0s_0s_1}, \lambda_{s_00s_1}, \lambda_{s_0s_10}$ and the six maps $\mu_{s00}, \mu_{0s0}, \mu_{00s}$.



For completeness, we mention some “non-examples”: collections of maps $\sigma_\alpha : \Delta^n \rightarrow X$ that satisfy conditions (1) and (2), but not condition (3) from Definition 1.2.2.

Example 1.2.4. Let $X = [0; 1]$ or more generally, any other non-discrete space, having infinitely many points. Then the collection of maps $\{\sigma_x : \Delta^0 \rightarrow X\}_{x \in X}$, $\sigma_x(1) = x$ satisfies (1) and (2), but not (3). We place one 0-simplex for each point of X , but points in $[0; 1]$ are not open.

Another example is as follows. Let X be the unit square $X = [0; 1] \times [0; 1]$. Consider, for each $y \in [0; 1]$, a map $\lambda_y : \Delta^0 \rightarrow X$, $\lambda_y(1) = (0, y)$, a map $\rho_y : \Delta^0 \rightarrow X$, $\rho_y(1) = (1, y)$ and a map $\sigma_y : \Delta^1 \rightarrow X$, $\sigma_y(t_0, t_1) = (t_0, y)$. In this way we place at height y one 1-simplex (as a horizontal segment), and two 0-simplices, as its left and right end. The collection of maps $\{\sigma_y, \lambda_y, \rho_y\}_{y \in [0; 1]}$ satisfies (1) and (2), but not (3).

Thus condition (3) precludes inadequate choices of maps σ_α , for example, covering a manifold (with boundary) of dimension n by simplices of smaller dimension. More generally, condition (3) is important when one needs to deal with infinite collections of simplices, in particular, when dealing with infinite-dimensional (in appropriate sense) spaces X .

Given a Δ -complex structure on X , we can recover the space just from the combinatorics of the maps $\{\sigma_\alpha : \Delta^{n(\alpha)} \rightarrow X\}_{\alpha \in A}$. More precisely, we can consider the disjoint union of simplices Δ_α^n , labelled by the respective maps σ_α . We then impose an equivalence relation \sim on the disjoint union: the i -th face of Δ_α^n is identified with Δ_β^{n-1} via the canonical order-preserving isomorphism if $\sigma_\alpha|_{[e_0, \dots, \widehat{e_i}, \dots, e_n]}$ coincides with $\sigma_\beta : \Delta^{n-1} \rightarrow X$ (under the canonical isomorphism).

The properties (1), (2), (3) from Definition 1.2.2 guarantee that the quotient space is indeed homeomorphic to X :

$$X \simeq \coprod_{\alpha \in A} \Delta_\alpha^n / \sim.$$

Turning this viewpoint backwards, we can consider X as being built up, inductively, by simplices of dimension 0, 1, 2, \dots , by imposing an equivalence relation, encoded combinatorially.

Example 1.2.5. Consider the Δ -complex structure on S^1 , discussed in Example 1.2.2. It gives an identification of S^1 as a quotient of $\Delta^0 \sqcup \Delta^1$, i.e.,

$$S^1 \simeq \Delta_0^0 \coprod \Delta_1^1 / \sim,$$

where the equivalence relation identifies the point Δ_0^0 with each of the endpoints of the 1-simplex Δ_1^1 .

Similarly, the Δ -complex structure on S^2 from Example 1.2.3 identifies S^2 with a quotient of

$$\underbrace{\Delta^0 \sqcup \dots \sqcup \Delta^0}_6 \coprod \underbrace{\Delta^1 \sqcup \dots \sqcup \Delta^1}_{12} \coprod \underbrace{\Delta^2 \sqcup \dots \sqcup \Delta^2}_8.$$

The equivalence relation is encoded in the maps, and can be made explicit by labelling each simplex with the respective map, e.g., $\Delta_{\mu_{s00}}^0$, $\Delta_{\mu_{0s0}}^0$, $\Delta_{\mu_{00s}}^0$, $\Delta_{\lambda_{0s_0s_1}}^1, \dots, \Delta_{\sigma_{s_0s_1s_2}}^2$.

One often constructs topological spaces as quotients, i.e., we write $X = Y / \sim$, where Y is a possibly simpler space. This is the case, for instance, for $X = S^1 \times S^1$, $X = \mathbb{RP}^2$, the Klein bottle, etc. In all of these examples $Y = [0; 1] \times [0; 1]$. One can try to build a Δ -complex structure on X by constructing first a Δ -complex structure on Y . We are going to see such examples in Section 1.4.

A Remark on Simplicial Complexes

The Δ -complex structure on S^1 from Example 1.2.2 involves one 1-simplex and one 0-simplex, and the gluing identifies the two vertices of Δ^1 . We could, however, choose different Δ -structures, e.g., one involving two (or more) 1-simplices – see Section 1.4. In that case each 1-simplex in X will have two distinct vertices – i.e., the maps $\sigma_\alpha : \Delta^1 \rightarrow S^1$ do not identify the vertices of Δ^1 . (Equivalently, the equivalence relation \sim does not identify distinct vertices.)

More generally, we say that a Δ -complex (structure on a topological space) X is a *simplicial complex* (structure on X) if all simplices are uniquely determined by their vertices. That is, for

all $n \in \mathbb{N}$ it is the case that each n -simplex in X has $n + 1$ distinct vertices and there are no other n -simplices with this set of vertices. Now, in such a situation, every face of an n -simplex in X is an $(n - 1)$ -simplex in X , and so on.

But such a structure is a completely combinatorial object! It is specified by a finite set – the 0-complexes of our Δ -structure, together with finite subsets (corresponding to simplices in X), having the property that all of their subsets are also simplices.

Here is the formal combinatorial description of a simplicial complex, given as the definition of an *abstract simplicial complex*.

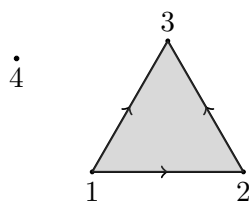
Definition 1.2.3 (Abstract Simplicial Complex). *Given a finite set $\{1, 2, \dots, m\} (= [m])$ an abstract simplicial complex is a collection \mathcal{K} of subsets of $[m]$, such that:*

1. $\emptyset \in \mathcal{K}$
2. $\{i\} \in \mathcal{K}$ (singletons are in \mathcal{K})
3. If $I \in \mathcal{K}$ and $J \subseteq I$, then $J \in \mathcal{K}$

The elements of $[m]$ are the vertices, and the elements of \mathcal{K} are the simplices, where $I \in \mathcal{K}$ is an $(|I| - 1)$ -simplex.

Sometimes, the condition $\emptyset \in \mathcal{K}$ is omitted. Abstract simplices are subsets of the power set of the given set of vertices, which are partially ordered by inclusion.

Example 1.2.6. Consider the following partially ordered set $V = \{1, 2, 3, 4\}$: The simplicial complex $\mathcal{K} = \{I = \{1, 2, 3\}, \{1, 2\}, \{1, 3\}, \{2, 3\}, \{1\}, \{2\}, \{3\}, \{4\}, \emptyset\}$



Given an abstract simplex \mathcal{K} , we can construct its *topological realization* as

$$|\mathcal{K}| = \bigcup_{\emptyset \neq I \in \mathcal{K}} (\text{Conv}(e_i), i \in I) \subseteq \mathbb{R}^m$$

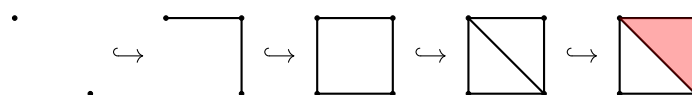
where $\{e_i\}$ is in the standard basis $e_1, \dots, e_m \in \mathbb{R}^m$.

Classically, homology theories were introduced for simplicial complexes (while Δ -complexes were also called semi-simplicial complexes). Simplicial complexes have simple combinatorial description and are widely used in computer implementations of homology calculations. For the purposes of human understanding, however, Δ -complexes are much more convenient.

A subcomplex of \mathcal{K} is a subset $L \subseteq \mathcal{K}$ that is also a simplicial complex. A *filtration* of complex \mathcal{K} is a nested subsequence of complexes:

$$\emptyset = \mathcal{K}^0 \subseteq \mathcal{K}^1 \subseteq \dots \mathcal{K}^m = \mathcal{K}$$

For generality, we let $\mathcal{K}^i = \mathcal{K}^m$ for all $i \geq m$. \mathcal{K} is called a filtered complex, and below there is a short example of a filtered complex:



1.3 Chain Complexes

Definition 1.3.1 (Chain complex). *Complex of abelian groups. Homology of a complex.*
A chain complex is a sequence of homomorphisms of abelian groups:

$$\dots \longrightarrow C_{n+1} \xrightarrow{\partial_{n+1}} C_n \xrightarrow{\partial_n} C_{n-1} \xrightarrow{\partial_{n-1}} \dots \longrightarrow C_1 \xrightarrow{\partial_1} C_0 \xrightarrow{\partial_0=0} 0$$

where $\partial_n \partial_{n+1} = 0$ for each n in \mathbb{Z} . The equation $\partial_n \partial_{n+1} = 0$ is equivalent to the inclusion $\text{Im } \partial_{n+1} \subset \ker \partial_n$.

The map ∂_n for a Δ -complex \mathcal{X} is a boundary homomorphism $\partial_n : \Delta_n(\mathcal{X}) \rightarrow \Delta_{n-1}(\mathcal{X})$ where the action on a basis element of $\Delta_n(\mathcal{X})$ is:

$$\partial_n(\sigma_\alpha) = \sum_i (-1)^i \sigma_\alpha | [v_0, \dots, \hat{v}_i, \dots, v_n]$$

where the ' $\hat{}$ ' symbol denotes the absence of that vertex.

Lemma 1.3.1. *The composition $\partial^2 = 0$ below is zero*

$$\Delta_n(X) \xrightarrow{\partial_n} \Delta_{n-1}(X) \xrightarrow{\partial_{n-1}} \Delta_{n-2}(X)$$

Proof: For $n = 3$:

$$\Delta_3(X) \xrightarrow{\partial_3} \Delta_2(X) \xrightarrow{\partial_2} \Delta_1(X)$$

Let us proof that $\partial_2 \partial_3 = 0$:

$$\partial_3 \sigma = \sum_i (-1)^i \sigma | [v_0, \dots, \hat{v}_i, v_3] = \sigma | [v_1, v_2, v_3] - \sigma | [v_0, v_2, v_3] + \sigma | [v_0, v_1, v_3] - \sigma | [v_0, v_1, v_2]$$

$$\begin{aligned} \partial_2 \partial_3(\sigma) &= \sigma | [v_2, v_3] - \sigma | [v_1, v_3] + \sigma | [v_1, v_2] \\ &= -\sigma | [v_2, v_3] + \sigma | [v_0, v_3] - \sigma | [v_0, v_2] \\ &= \sigma | [v_1, v_3] - \sigma | [v_0, v_3] + \sigma | [v_0, v_1] \\ &= -\sigma | [v_1, v_2] + \sigma | [v_0, v_2] - \sigma | [v_0, v_1] = 0 \end{aligned} \tag{1.1}$$

In case of n :

$$\begin{aligned} \partial_{n-1} \partial_n(\sigma) &= \partial_{n-1} \left(\sum_i (-1)^i \sigma | [v_0, \dots, \hat{v}_i, \dots, v_n] \right) \\ &= \sum_j (-1)^j \left(\sum_i (-1)^i \sigma | [v_0, \dots, \hat{v}_i, \dots, v_n] \right) | [v_0, \dots, \hat{v}_j, \dots, v_n] \\ &= \sum_{j < i} (-1)^i (-1)^j \sigma | [v_0, \dots, \hat{v}_j, \dots, \hat{v}_i, \dots, v_n] + \sum_{j > i} (-1)^i (-1)^j \sigma | [v_0, \dots, \hat{v}_i, \dots, \hat{v}_j, \dots, v_n] = 0 \end{aligned} \tag{1.2}$$

Remark: Chain complexes can be also defined over R -modules, where R is a commutative ring:

Definition 1.3.2. (Chain complex of R -module) A Chain complex of R -modules is a sequence:

$$(C_\bullet, d_\bullet) = (\dots \longrightarrow C_{n+1} \xrightarrow{d_{n+1}} C_n \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \dots)$$

where for each $n \in \mathbb{Z}$, C_n is an R -module and $d_n \in \text{Hom}_R(C_n, C_{n-1})$ satisfies $d_n \circ d_{n+1} = 0$

In chain complexes of R -modules, n is the degree of the R -module C_n . The R -linear maps $d_n (n \in \mathbb{Z})$ are called differential maps.

Also, a complex C_\bullet is called non-negative (resp. positive) if $C_n = 0$, for all $n \in \mathbb{Z}_{<0}$ (resp. $n \in \mathbb{Z}_{\leq 0}$)

Chain complexes together with morphisms of chain complexes (and composition given by degree-wise composition of R -morphisms) form a category, which we will denote by $Ch(RMod)$

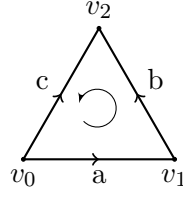
1.4 Homology Calculations: Examples

In the first example of Homology calculations, it is important to notice that the homology groups are calculated in two methods, with different Δ -structure on S^1 . Even though, the circle is parameterized by different Δ -complex structures, the calculations below show that the Homology groups are the same.

1.4.1 S^1

Method I: Triangulation

To compute the homology group of the circle S^1 we can triangulate the circle in the following way:



We can construct the following chain complex which is a sequence of homomorphisms of abelian groups:

$$0 \xrightarrow{\partial_2=0} C_1 \xrightarrow{\partial_1} C_0 \xrightarrow{\partial_0=0} 0$$

where $\partial_n \partial_{n+1} = 0$ for each n in \mathbb{Z} and

$$\begin{cases} C_0 = \langle v_0, v_1, v_2 \rangle \\ C_1 = \langle a, b, c \rangle \\ C_n = \{0\} \quad \forall n \geq 2 \end{cases},$$

$$0 \xrightarrow{\partial_2=0} \mathbb{Z}^{\oplus 3} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 3} \xrightarrow{\partial_0=0} 0$$

The n -th homology group is defined as $H_n = \frac{\ker \partial_n}{\text{Im } \partial_{n+1}}$.

First, let's compute H_0 :

$\ker \partial_0 = C_0 = \langle v_0, v_1, v_2 \rangle$ since $\partial_0 = 0$

To calculate $\text{Im } \partial_1$, let's compute $\partial_1(\alpha a + \beta b + \gamma c) = \alpha(v_1 - v_0) + \beta(v_2 - v_1) - \gamma(v_2 - v_0)$
 $= (-\alpha + \gamma)v_0 + (\alpha - \beta)v_1 + (\beta - \gamma)v_2 = (\gamma - \alpha)v_0 + (\alpha - \beta)v_1 + (-\gamma + \alpha)v_2$

$$\text{Im } \partial_1 = \left\{ \begin{pmatrix} \gamma - \alpha \\ \alpha - \beta \\ -(\gamma - \alpha) - (\alpha - \beta) \end{pmatrix}, \quad \alpha, \beta, \gamma \in \mathbb{Z} \right\} \subseteq \mathbb{Z}^{\oplus 3}$$

Claim : There exist an isomorphism $\psi : \text{Im } \partial_1 \simeq \mathbb{Z}^2$

$$\psi : \begin{pmatrix} \gamma - \alpha \\ \alpha - \beta \\ \beta - \gamma \end{pmatrix} \mapsto \begin{pmatrix} \gamma - \alpha \\ \alpha - \beta \end{pmatrix}$$

ψ is one-to-one since if $(\gamma - \alpha = 0 \ \& \ \alpha - \beta = 0) \Rightarrow \beta - \gamma = 0 \ \& \ \alpha = \beta = \gamma$

ψ is onto since given $\begin{pmatrix} m \\ n \end{pmatrix} \in \mathbb{Z}^2$ there exist an element $\begin{pmatrix} m \\ n \\ -m - n \end{pmatrix} \in \text{Im } \partial_1$ such that

$$\psi \left(\begin{pmatrix} m \\ n \\ -m - n \end{pmatrix} \right) = \begin{pmatrix} m \\ n \end{pmatrix}, \text{ since } \psi \text{ is one-to-one and onto, } \text{Im } \partial_1 \simeq \mathbb{Z}^2$$

$$H_0 = \frac{\ker \partial_0}{\text{Im } \partial_1} = \mathbb{Z}^3 / \left(\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \mathbb{Z} \oplus \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \mathbb{Z} \right)$$

$$\text{Claim: } \phi : \left(\mathbb{Z}^3 / \left(\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \mathbb{Z} \oplus \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \mathbb{Z} \right) \right) \simeq \mathbb{Z}$$

First, let us take the map $\varphi : \mathbb{Z}^3 \rightarrow \mathbb{Z}^3 / \left\langle \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \right\rangle$

$$\mathbb{Z}^3 \ni \begin{pmatrix} p \\ q \\ r \end{pmatrix} = p \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} + q \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} + (p+q+r) \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\text{where } p \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} + q \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \in \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \mathbb{Z} + \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \mathbb{Z}$$

$$\text{So, } \varphi : \begin{pmatrix} p \\ q \\ r \end{pmatrix} \mapsto \begin{pmatrix} p \\ q \\ r \end{pmatrix} = (p+q+r) \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Finally, $\phi : \begin{pmatrix} p \\ q \\ r \end{pmatrix} \mapsto (p+q+r) \in \mathbb{Z}$, Clearly, ϕ is injective and surjective.

So, $H_0 \simeq \mathbb{Z}$

Second, let's compute H_1 :

$$\ker \partial_1 = \left\{ \begin{pmatrix} m \\ m \\ m \end{pmatrix}, m \in \mathbb{Z} \right\} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \mathbb{Z} \simeq \mathbb{Z}$$

$$\text{Im } \partial_2 = \{0\} \text{ since } C_2 = \{0\}$$

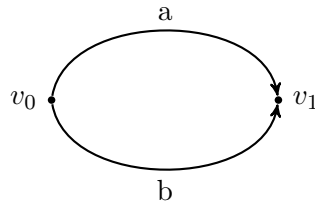
$$H_1 = \frac{\ker \partial_1}{\text{Im } \partial_2} = \frac{\ker \partial_1}{\{0\}} = \ker \partial_1 \simeq \mathbb{Z}$$

Finally, the homology groups of the circle are:

$$H_n^\Delta(S^1) \simeq \begin{cases} \mathbb{Z}, & \text{for } n = 0, 1 \\ 0 & \text{for } n \geq 2 \end{cases}$$

Method II

To compute the homolgy group of the circle S^1 we can construct the circle, by two vertices and two edges, in the following way:



We can construct the following chain complex which is a sequence of homomorphisms of abelian groups:

$$0 \xrightarrow{\partial_2=0} C_1 \xrightarrow{\partial_1} C_0 \xrightarrow{\partial_0=0} 0$$

where $\partial_n \partial_{n+1} = 0$ for each n in \mathbb{Z} and

$$\begin{cases} C_0 = \langle v_0, v_1 \rangle \\ C_1 = \langle a, b \rangle \\ C_n = \{0\} \quad \forall n \geq 2 \end{cases},$$

$$0 \xrightarrow{\partial_2=0} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_0=0} 0$$

The n -th homology group is defined as $H_n = \frac{\ker \partial_n}{\text{Im } \partial_{n+1}}$.

First, let's compute H_0 :

$\ker \partial_0 = C_0 = \langle v_0, v_1 \rangle$ since $\partial_0 = 0$

To calculate $\text{Im } \partial_1$, let's compute $\partial_1(\alpha a + \beta b) = \alpha(v_1 - v_0) + \beta(v_1 - v_0) = (\alpha + \beta)(v_1 - v_0)$

$\text{Im } \partial_1 = \langle v_1 - v_0 \rangle$

$$H_0 = \frac{\ker \partial_0}{\text{Im } \partial_1} = \frac{\langle v_0, v_1 \rangle}{\langle v_1 - v_0 \rangle} = \frac{\langle v_1 - v_0, v_1 \rangle}{\langle v_1 - v_0 \rangle} = \langle v_1 \rangle \simeq \mathbb{Z}$$

Second, let's compute H_1 :

$\ker \partial_1 = \langle a - b \rangle$ since $\partial_1(\alpha a + \beta b) = (\alpha + \beta)(v_1 - v_0) = 0 \implies \alpha = -\beta$ so the kernel is generated by the element $(a - b)$

$\text{Im } \partial_2 = \{0\}$ since $C_2 = \{0\}$

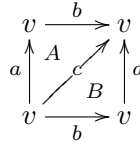
$$H_1 = \frac{\ker \partial_1}{\text{Im } \partial_2} = \frac{\ker \partial_1}{\{0\}} = \ker \partial_1 \simeq \mathbb{Z}$$

Finally, the homology groups of the circle with a different Δ -complex on it are the same:

$$H_n^\Delta(S^1) \simeq \begin{cases} \mathbb{Z}, & \text{for } n = 0, 1 \\ 0 & \text{for } n \geq 2 \end{cases}$$

1.4.2 Torus

One way to calculate the homology groups of a torus T is by triangulating it into two 2-simplices A and B , upper triangle and lower one respectively.



We can construct the following chain complex which is a sequence of homomorphisms of abelian groups:

$$0 \xrightarrow{\partial_3=0} C_2 \xrightarrow{\partial_2} C_1 \xrightarrow{\partial_1} C_0 \xrightarrow{\partial_0=0} 0$$

where $\partial_n \partial_{n+1} = 0$ for each n in \mathbb{Z} and

$$\begin{cases} C_0 = \langle v \rangle \\ C_1 = \langle a, b, c \rangle \\ C_2 = \langle A, B \rangle \\ C_n = \{0\} \quad \forall n \geq 3 \end{cases},$$

$$0 \xrightarrow{\partial_3=0} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_2} \mathbb{Z}^{\oplus 3} \xrightarrow{\partial_1} \mathbb{Z} \xrightarrow{\partial_0=0} 0$$

The n -th homology group is defined as $H_n = \frac{\ker \partial_n}{\text{Im } \partial_{n+1}}$.

First, let's compute H_0 :

$\ker \partial_0 = C_0 = \langle v \rangle$ since $\partial_0 = 0$

$\text{Im } \partial_1 = \{0\}$ since $\partial_1(\alpha a + \beta b + \gamma c) = \alpha(v - v) + \beta(v - v) + \gamma(v - v) = 0$
 $H_0 = \frac{\ker \partial_0}{\text{Im } \partial_1} = C_0 \simeq \mathbb{Z}$

Second, let's compute H_1 :

$\ker \partial_1 = C_1 = \langle a, b, c \rangle$ since $\partial_1 = 0$

$\text{Im } \partial_2 = \langle a + b - c \rangle$ since $\partial_2(\alpha A + \beta B) = \alpha(a + b - c) + \beta(a + b - c) = (\alpha + \beta)(a + b - c)$

$H_1 = \frac{\ker \partial_1}{\text{Im } \partial_2} = \frac{\langle a, b, c \rangle}{\langle a + b - c \rangle}$

The group $\langle a, b, c \rangle$ can be also generated by the elements $m = a + b - c$, b and c where $a = m - b + c$.

So,

$H_1 = \frac{\langle a + b - c, b, c \rangle}{\langle a + b - c \rangle} = \langle b, c \rangle \simeq \mathbb{Z} \oplus \mathbb{Z}$

Last, let's compute H_2 :

$\ker \partial_2 = \langle A - B \rangle$ since $\partial_2(\alpha A + \beta B) = (\alpha + \beta)(a + b - c) = 0 \implies \alpha = -\beta$ so the kernel is generated by the element $A - B$

$\text{Im } \partial_3 = \{0\}$ since $C_3 = \{0\}$

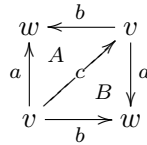
$H_2 = \frac{\ker \partial_2}{\text{Im } \partial_3} = \frac{\langle A - B \rangle}{\{0\}} = \langle A - B \rangle \simeq \mathbb{Z}$

Finally, the homology groups of the torus are:

$$H_n^\Delta(T) \simeq \begin{cases} \mathbb{Z}, & \text{for } n = 0, 2 \\ \mathbb{Z} \oplus \mathbb{Z}, & \text{for } n = 1 \\ 0 & \text{for } n \geq 3 \end{cases}$$

1.4.3 \mathbb{RP}^2

One way to calculate the homology groups of a projective plane \mathbb{RP}^2 is by triangulating it into two 2-simplices A and B, upper triangle and lower one respectively.



We can construct the following chain complex which is a sequence of homomorphisms of abelian groups:

$$0 \xrightarrow{\partial_3=0} C_2 \xrightarrow{\partial_2} C_1 \xrightarrow{\partial_1} C_0 \xrightarrow{\partial_0=0} 0$$

where $\partial_n \partial_{n+1} = 0$ for each n in \mathbb{Z} and

$$\begin{cases} C_0 = \langle v, w \rangle \\ C_1 = \langle a, b, c \rangle \\ C_2 = \langle A, B \rangle \\ C_n = \{0\} \quad \forall n \geq 3 \end{cases},$$

$$0 \xrightarrow{\partial_3=0} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_2} \mathbb{Z}^{\oplus 3} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_0=0} 0$$

The n -th homology group is defined as $H_n = \ker \partial_n / \text{Im } \partial_n$

First, let's compute H_0 :

$\ker \partial_0 = C_0 = \langle v, w \rangle$ since $\partial_0 = 0$

$\text{Im } \partial_1 = \langle w - v \rangle$ since $\partial_1(\alpha a + \beta b + \gamma c) = \alpha(w - v) + \beta(w - v) + \gamma(v - v) = (\alpha + \beta)(w - v)$

$$H_0 = \frac{\ker \partial_0}{\text{Im } \partial_1} = \frac{\langle v, w \rangle}{\langle w-v \rangle} = \frac{\langle w-v, w \rangle}{\langle w-v \rangle} = \langle w \rangle \simeq \mathbb{Z}$$

Second, let's compute H_1 :

$$\ker \partial_1 = \langle a-b, c \rangle \text{ since } \partial_1(\alpha a + \beta b + \gamma c) = (\alpha + \beta)(w-v) = 0 \implies \alpha = -\beta$$

The general element in C_1 : $(\alpha a + \beta b + \gamma c) = \alpha(a-b) + \gamma c$, so the $\ker \partial_1$ can be generated by the elements $a-b$ and c

$$\text{Im } \partial_2 = \langle -a+b+c, a-b+c \rangle \text{ since } \partial_2(\alpha A + \beta B) = \alpha(-a+b+c) + \beta(a-b+c)$$

$$H_1 = \frac{\ker \partial_1}{\text{Im } \partial_2} = \frac{\langle a-b, c \rangle}{\langle -a+b+c, a-b+c \rangle}$$

The group $\langle a-b, c \rangle$ can be also generated by the elements $m = a-b+c$, and c where $a-b = m-c$. So,

$$H_1 = \frac{\langle a-b, c \rangle}{\langle -a+b+c, a-b+c \rangle} = \frac{\langle a-b+c, c \rangle}{\langle a-b+c, -a+b+c \rangle}$$

If we let $t = a-b+c$ then $-a+b+c = -t+2c$ then the group $\langle t, -t+2c \rangle$ can be also generated by the elements t and $2c$.

$$\text{In terms of } t \text{ and } c, H_1 = \frac{\langle t, c \rangle}{\langle t, 2c \rangle} = \frac{\langle c \rangle}{\langle 2c \rangle} \simeq \frac{\mathbb{Z}}{2\mathbb{Z}}$$

Last, let's compute H_2 :

$$\ker \partial_2 = \{0\} \text{ since } \partial_2(\alpha A + \beta B) = (-\alpha + \beta)a + (\alpha - \beta)b + (\alpha + \beta)c = 0 \text{ only when } \alpha = \beta = 0$$

$$\text{Im } \partial_3 = \{0\} \text{ since } C_3 = \{0\}$$

$$H_2 = \frac{\ker \partial_2}{\text{Im } \partial_3} = \frac{\{0\}}{\{0\}} = 0$$

Finally, the homology groups of the projective plane are:

$$H_n^\Delta(\mathbb{RP}^2) \simeq \begin{cases} \mathbb{Z}, & \text{for } n = 0 \\ \frac{\mathbb{Z}}{2\mathbb{Z}}, & \text{for } n = 1 \\ 0 & \text{for } n \geq 2 \end{cases}$$

1.5 Maps of Complexes

In the previous sections, we considered boundary homomorphisms between abelian groups as part of a chain complex. In this section, we will draw our attention to maps between chain complexes.

Definition 1.5.1. (*Maps of Chain Complexes*)

Let (C_\bullet, ∂) and (D_\bullet, δ) be two chain complexes. A map of chain complexes is a morphism f that is a sequence of homomorphisms $(f_n)_{n \in \mathbb{Z}}$:

$$\begin{array}{ccccccc} (C_\bullet, \partial) & C_\bullet & \dots & \longrightarrow & C_n & \xrightarrow{\partial_n} & C_{n-1} & \xrightarrow{\partial_{n-1}} & C_{n-2} & \xrightarrow{\partial_{n-2}} & \dots & C_\bullet \\ & & & & \downarrow f_n & & \downarrow f_{n-1} & & \downarrow f_{n-2} & & & \\ (D_\bullet, \delta) & D_\bullet & \dots & \longrightarrow & D_n & \xrightarrow{\delta_n} & D_{n-1} & \xrightarrow{\delta_{n-1}} & D_{n-2} & \xrightarrow{\delta_{n-2}} & \dots & D_\bullet \end{array}$$

$$f_n : C_n \rightarrow D_n \quad \text{s.t.} \quad f_{n-1} \circ \partial_n = \delta_n \circ f_n \quad \forall n \in \mathbb{Z}$$

$$\begin{array}{ccc} C_n & \xrightarrow{\partial_n} & C_{n-1} \\ \downarrow f_n & & \downarrow f_{n-1} \\ D_n & \xrightarrow{\delta_n} & D_{n-1} \end{array} \quad \text{commutes.}$$

1.5.1 Maps on Homology

A homomorphism of chain complexes induces a homomorphism on the homology. The induced map can be defined as:

$$\begin{aligned} H_n(f) : H_n(C_\bullet) &\rightarrow H_n(D_\bullet) \\ H_n(f) : [x] &\mapsto [f_n(x)] \end{aligned}$$

To prove the claim above it is enough to check that $H_n(f)$ is well-defined. We can prove well-defines by checking if cycles are sent to cycles and boundaries to boundaries.

(1) Let us take a cycle $x \in C_n$, so that $x \in \ker(\partial_n)$, $\partial_n(x) = 0$

$$\begin{aligned} \delta_n \circ f_n(x) &= f_{n-1} \circ \partial_n(x) = f_{n-1}(0) = 0 \Rightarrow f_n(x) \in \ker \delta_n, f_n(x) \text{ is a cycle} \\ &\Rightarrow f_n(\ker \partial_n) \subseteq \ker \delta_n \end{aligned}$$

So, cycles are sent to cycles.

(2) Let us take a boundary $y \in C_n$, so that $y \in \text{Im } \partial_{n+1} \Rightarrow \exists z \in C_{n+1}$ such that $\partial_{n+1}(z) = y$

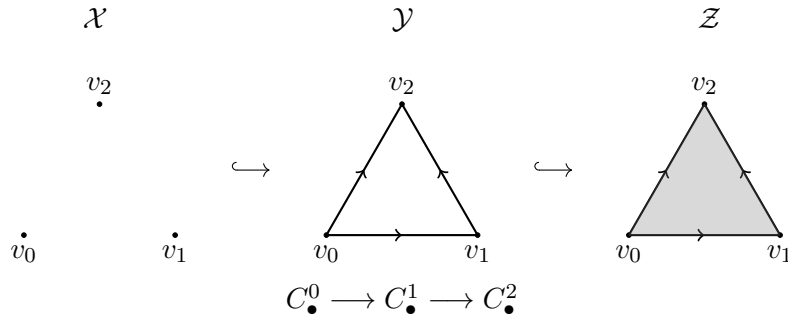
$$\begin{aligned} f_n(y) &= f_n(\partial_{n+1}(z)) = \delta_{n+1}(f_{n+1}(z)) \\ &\Rightarrow f_n(y) \in \text{Im } \delta_{n+1} f_n(y) \text{ is a boundary} \\ &\Rightarrow f_n(\text{Im } \partial_{n+1}) \subseteq \text{Im } (\delta_{n+1}) \end{aligned}$$

So, boundaries are sent to boundaries.

$$\begin{aligned} H_n(f) : H_n(C_\bullet) &\rightarrow H_n(D_\bullet) \\ H_n(f) : \ker \partial_n / \text{Im } (\partial_{n+1}) &\rightarrow \ker \delta_n / \text{Im } (\delta_{n+1}) \\ [x] &\mapsto [f_n(x)] \\ x + \text{Im } \partial_{n+1} &\mapsto f_n(x) + f_n(\text{Im } \delta_{n+1}) = f_n(x) + \text{Im } (\delta_{n+1}) = [f_n(x)] \end{aligned}$$

□

Let us consider an example between maps of complexes defined by the three spaces below.



Maps between complexes:

$$C_{\bullet}^0 \longrightarrow C_{\bullet}^1 \longrightarrow C_{\bullet}^2$$

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 2 & & 0 & \longrightarrow & 0 & \longrightarrow & \mathbb{Z} \\
 & & \downarrow \partial_2^0=0 & & \downarrow \partial_2^1=0 & & \downarrow \partial_2^2=\begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix} \\
 1 & & 0 & \longrightarrow & \mathbb{Z}^3 & \longrightarrow & \mathbb{Z}^3 \\
 & & \downarrow \partial_1^0=0 & & \downarrow \partial_1^1=\partial_1^2 & & \downarrow \partial_1^2=\begin{pmatrix} -1 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \\
 0 & & \mathbb{Z}^3 & \longrightarrow & \mathbb{Z}^3 & \longrightarrow & \mathbb{Z}^3 \\
 & & \downarrow \partial_0^0=0 & & \downarrow \partial_0^1=0 & & \downarrow \partial_0^2=0 \\
 & & 0 & & 0 & & 0
 \end{array}$$

Induced maps on homology:

$$H(C_{\bullet}^0) \longrightarrow H(C_{\bullet}^1) \longrightarrow H(C_{\bullet}^2)$$

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 2 & & 0 & \longrightarrow & 0 & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 1 & & 0 & \longrightarrow & \mathbb{Z} & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & & \mathbb{Z}^3 & \longrightarrow & \mathbb{Z} & \longrightarrow & \mathbb{Z} \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

Chapter 2

Singular Homology and Homotopy Invariance

In the previous chapter, we considered a parameterization of a space by simplexes, where the maps $\sigma_\alpha : \Delta^n \rightarrow X$ had restrictions defined in 1.2.2. If we only require that the σ map is continuous, then by definition that would be a singular n – *simplex* in a space X . The lack of other restrictions on the map $\sigma : \Delta^n \rightarrow X$, convey that σ does not need to be a ‘nice’ embedding, in fact it can have singularities, where its image does not look like a simplex.

$C_n(X)$ is a free abelian group with generators the set of singular n – *simplexes* in X : the continuous maps $\sigma : \Delta^n \rightarrow X$. The elements of $C_n(X)$ are singular n – *chains* defined as $\sum_i (n_i \sigma_i)$ for $n_i \in \mathbb{Z}$. The boundary operator $\partial_n : C_n(X) \rightarrow C_{n-1}(X)$ is defined the same way as in simplicial n – *chains*, by the formula:

$$\partial_n(\sigma) = \sum_i (-1)^i \sigma| [v_0, \dots, \hat{v}_i, \dots, v_n]$$

By preserving the order of the vertices, the $\sigma| [v_0, \dots, \hat{v}_i, \dots, v_n]$ is identified with the map $\Delta^{n-1} \rightarrow X$. The proof of lemma 1.3.1, $\partial_2 = 0$, holds true also for singular simplexes. Therefore, the singular homology group is defined the same way: $H_n(X) = \ker \partial_n / \text{Im } \partial_{n+1}$. The elements in the \ker are singular cycles, and the elements in the Im singular boundaries.

Let us consider some explicit examples of $C_n(X)$:

- For a topological space X : $C_0(X)$ consists of all maps $\sigma : \Delta^0 \rightarrow X$, which means that $C_0(X)$ is a free group on the points of X .
- If $X = \mathbb{R}$: $C_1(X)$ consists of all maps $\sigma : \Delta^1 \rightarrow \mathbb{R}$, which means that $C_0(X)$ is a free group on continuous maps:

$$[0, 1] \simeq \Delta^1 \rightarrow \mathbb{R}$$

In this case $C_1(X)$ can be considered as a vector space with vectors the maps: $[0, 1] \rightarrow \mathbb{R}$.

From the examples above, it is clear that the groups $C_n(X)$ can be so large to the point where the number of singular n – *simplexes* in a space X is uncountable. It is not easy to see that even in singular homology where X is generated by a finite number of simplexes, $H_n(X)$ should be finite generated for all n , and that $H_n(X)$ should be 0 for $n > \dim(X)$.

At first glance, singular homology seems to be more general than simplicial homology, however if for an arbitrary space X , we define the singular complex $S(X)$ as a Δ – *complex* with one n – *simplex* Δ_σ^n for each singular n – *simplex* $\sigma : \Delta^n \rightarrow X$, then $H_n^\Delta(S(X))$ is the same as $H_n(X)$. In this case singular homology can be viewed as a special case of simplicial homology.

2.1 Homotopy invariance

A significant result that can be proven by singular homology is that if two spaces X, Y are homeomorphic, the singular homology groups are isomorphic $H_n(X) \simeq H_n(Y)$.

More generally, A continuous map $f : X \rightarrow Y$ induces a chain map: $f_\# : C_n(X) \rightarrow C_n(Y)$.

$$f_\#(\sigma : \Delta^n \rightarrow X) = f \circ \sigma$$

$$\Delta^n \xrightarrow{\sigma} X \xrightarrow{f} Y$$

The boundary operator of $f_\#$ is equal to $\partial_n(f \circ \sigma) = f \circ \partial_n(\sigma)$.

$$H_n(f_\#) = f_* : H_n(X) \rightarrow H_n(Y)$$

If we additionally require f to be a bijection and have a continuous inverse f^{-1} , so f is a homeomorphism, then $f_\# : C_n(X) \simeq C_n(Y)$

$$\sigma \mapsto f \circ \sigma$$

$$\mu \circ f^{-1} \leftarrow \mu$$

Then the induced singular homology map $f_* : H_n(X) \simeq H_n(Y)$ defines an isomorphism.

Moreover,

$$f_* \text{ preserves composition, } (f \circ g)_* = f_* \circ g_* \quad (2.1)$$

$$f_* \text{ preserves the identity, } id : X \rightarrow Y \text{ goes to } id_* : H_n(X) \rightarrow H_n(Y) \quad (2.2)$$

Category Theory Interpretation: If we consider Top to be the category of topological spaces where maps are continuous:

$$Hom_{Top}(X, Y) = \{f : X \rightarrow Y, f \text{ is continuous}\},$$

and Ab the category of abelian groups where maps are group homomorphisms:

$$Hom_{Ab}(G, H) = \{\phi : G \rightarrow H, \phi \text{ is group homomorphism}\}$$

then for each $n \geq 0$:

$$H_n : Top \rightarrow Ab$$

$$X \rightsquigarrow H_n(X)$$

$$f : X \rightarrow Y \rightsquigarrow f_* : H_n(X) \rightarrow H_n(Y)$$

H_n is a functor and (2.1) (2.2) hold.

If we also consider the category, Homotopic Topology $HoTop$ of topological spaces where maps are continuous up to homotopy, then we obtain the following commutative diagram:

$$\begin{array}{ccc} Top & \xrightarrow{H_n} & Ab \\ \downarrow & \nearrow & \\ HoTop & & \end{array}$$

$$Hom_{HoTop}(X, Y) = Hom_{Top}(X, Y) / \simeq$$

Remark: The continuous maps $f, g : X \rightarrow Y$ are homotopic if

$$\exists H : X \times [0, 1] \rightarrow Y,$$

$$\text{for } x \in X \text{ and } t \in [0, 1] : H(x, t) = H_t(x)$$

$$\text{s.t } H(x, 0) = f(x) \text{ and } H(x, 1) = g(x)$$

$$\text{i.e } H|_{x \times \{0\}} = f \text{ and } H|_{x \times \{1\}} = g$$

Let us consider some explicit homotopic maps:

- $f, g : \mathbb{R} \rightarrow \mathbb{R}$ where $f = id, f(x) = x \forall x \in X$, and $g = 0, g(x) = 0 \forall x \in X$
 $H : \mathbb{R} \times [0, 1] \rightarrow \mathbb{R}$
 $H(x, t) = (1 - t)x$, clearly $H(x, 0) = x$ and $H(x, 1) = 0$
- $f, g : S^1 \rightarrow \mathbb{R}^2$ where f is an inclusion, $f(x, y) = (x, y) \forall (x, y) \in S^1$, and $g = 0, g(x, y) = 0 \forall (x, y) \in S^1$
 $H : S^1 \times [0, 1] \rightarrow \mathbb{R}^2$
 $H(x, y, t) = (1 - t)\langle x, y \rangle$, clearly $H(x, y, 0) = \langle x, y \rangle$ and $H(x, y, 1) = 0$

If $f, g : X \rightarrow Y$ are homotopic, then the induced maps on homology $f_*, g_* : H_n(X) \rightarrow H_n(Y)$, are the same $f_* = g_* \forall n$

Define $p_n : C_n^{sing}(X) \rightarrow C_n^{sing}(Y)$ s.t $f_{\#} - g_{\#} = \partial p + p \partial$

$$\begin{array}{ccccc}
 C_{n+1}(X) & \xrightarrow{\partial_{n+1}} & C_n(X) & \xrightarrow{\partial_n} & C_{n-1}(X) \\
 \downarrow f_{n+1} & & \downarrow f_n & & \downarrow f_{n-1} \\
 C_{n+1}(Y) & \xrightarrow{\delta_{n+1}} & C_n(Y) & \xrightarrow{\delta_n} & C_{n-1}(Y)
 \end{array}$$

$\begin{array}{c} \nearrow p_n \quad \nearrow p_{n-1} \\ \searrow g_{n+1} \quad \searrow g_n \quad \searrow g_{n-1} \end{array}$

For $\sigma : \Delta^n \rightarrow X$ the map $p_n(\sigma) : \Delta^{n+1} \rightarrow Y$ should be a continuous map.
 $H : X \times [0, 1] \rightarrow Y, H|_{x \times \{0\}} = f$ and $H|_{x \times \{1\}} = g$

$$\Delta^n \times [0, 1] \xrightarrow{\sigma \times 1} X \times [0, 1] \xrightarrow{H} Y$$

The idea is to write $\Delta^n \times [0, 1]$ as union of Δ^{n+1} . Let us consider some explicit examples of the p maps:

- $p_0 : C_0(X) \rightarrow C_1(Y)$
 $p_0(\sigma) = H_0(\sigma \times 1)|_{[v_0 w_0]} : \Delta^1 \rightarrow Y$
We can parameterize Δ^1 , as $\Delta^1 = \{(t_0, t_1) | t_0 + t_1 = 1, t_0, t_1 \geq 0\}$
 $\Delta^1 = \{1\} \subseteq \mathbb{R}, \sigma(1) = q$

$$\begin{aligned}
 \Delta^0 \times [0, 1] &\simeq \Delta^1 \\
 \{1\} \times \{t\} &\mapsto (1 - t, t) \\
 \sigma \times 1 : (1, t) &\mapsto (\sigma(1), t) \\
 H_0(\sigma \times 1) : (1, t) &\mapsto H(q, t), \text{ where } H(q, 0) = f(q), H(q, 1) = g(q)
 \end{aligned}$$

- $p_1 : C_1(X) \rightarrow C_2(Y)$
 $p_1(\sigma) = \sum_{i=0}^1 H_0(\sigma \times 1)|_{[v_0 \dots w_i]} = H_0(\sigma \times 1)|_{[v_0 w_0 w_1]} - H_0(\sigma \times 1)|_{[v_0 v_1 w_1]}$

$$\begin{aligned}
 \Delta^1 \times [0, 1] &\simeq [0, 1] \times [0, 1] \\
 ((t_0, t_1), t) &\mapsto (t_0, t) \\
 \sigma \times 1 : (1, t) &\mapsto (\sigma(1), t) \\
 H_0(\sigma \times 1) : (1, t) &\mapsto H(q, t), \text{ where } H(q, 0) = f(q), H(q, 1) = g(q)
 \end{aligned}$$

$$\begin{array}{ccccccc}
C_2(X) & \xrightarrow{\partial_2} & C_1(X) & \xrightarrow{\partial_1} & C_0(X) & \xrightarrow{\partial_0} & 0 \\
& & \downarrow f & & \downarrow g & & \\
& \swarrow p_1 & & \swarrow p_0 & & & \\
C_2(Y) & \xrightarrow{\delta_2} & C_1(Y) & \xrightarrow{\delta_1} & C_0(Y) & \xrightarrow{\delta_0} & 0
\end{array}$$

From the diagram above: $\delta_2 p_1 + p_0 \partial_1 : C_1(X) \rightarrow C_1(Y)$

$$\begin{aligned}
(p_0 \circ \partial_1)(\sigma) &= p_0(\sigma|_{[v_1]} - \sigma|_{[v_0]}) \\
&= H_0(\sigma \times 1)|_{[v_1 w_1]} - H_0(\sigma \times 1)|_{[v_0 w_0]} \\
&= H_0(\sigma|_{[v_1]} \times 1)|_{[v_1 w_1]} - H_0(\sigma|_{[v_0]} \times 1)|_{[v_0 w_0]} \\
&= H_0(\sigma \times 1)|_{[v_1] \times [0,1]} - H_0(\sigma \times 1)|_{[v_0] \times [0,1]}
\end{aligned}$$

$$\begin{aligned}
(\delta_2 \circ p_1)(\sigma) &= \delta_2(H_0(\sigma \times 1)|_{[v_0 w_0 w_1]} - H_0(\sigma \times 1)|_{[v_0 v_1 w_1]}) \\
&= H_0(\sigma \times 1)|_{[w_0 w_1]} - H_0(\sigma \times 1)|_{[v_0 w_1]} + H_0(\sigma \times 1)|_{[v_0 w_0]} \\
&\quad - H_0(\sigma \times 1)|_{[v_1 w_1]} + H_0(\sigma \times 1)|_{[v_0 w_1]} - H_0(\sigma \times 1)|_{[v_0 v_1]}
\end{aligned}$$

So , $(\delta_2 p_1 + p_0 \partial_1)(\sigma) = H_0(\sigma \times 1)|_{[w_0 w_1]} - H_0(\sigma \times 1)|_{[v_0 v_1]} = g \circ \sigma - f \circ \sigma = (g - f) \circ \sigma$

$$\Rightarrow \delta_2 p_1 + p_0 \partial_1 = g - f$$

Theorem 2.1.1. *If two chain maps $f_\bullet, g_\bullet : (C_\bullet, \partial) \rightarrow (D_\bullet, \delta)$ are chain-homotopic then they induce the same homomorphism on homology:*

More explicitly:

$$\begin{array}{ccccccc}
\cdots & \xrightarrow{\partial_{n+2}} & C_{n+1} & \xrightarrow{\partial_{n+1}} & C_n & \xrightarrow{\partial_n} & C_{n-1} & \xrightarrow{\partial_{n-1}} & \cdots \\
& & \downarrow f_{n+1} & & \downarrow f_n & & \downarrow f_{n-1} & & \\
& \swarrow p_{n+1} & & \swarrow p_n & & \swarrow p_{n-1} & & \swarrow p_{n-2} & \\
\cdots & \xrightarrow{\delta_{n+2}} & D_{n+1} & \xrightarrow{\delta_{n+1}} & D_n & \xrightarrow{\delta_n} & D_{n-1} & \xrightarrow{\delta_{n-1}} & \cdots
\end{array}$$

$$H_n(f) : H_n(C_\bullet) \rightarrow H_n(D_\bullet)$$

$$H_n(f) : [x] \mapsto [f_n(x)]$$

If $f_n - g_n = \delta_{n+1} p_n + p_{n-1} \partial_n \Rightarrow H_n(f) = H_n(g)$

Proof: Let us proof that the maps f_n, g_n induce the same homology.

For any $x \in \ker \partial_n \Rightarrow \partial_n x = 0$,

$$(f_n - g_n)(x) = \delta_{n+1} p_n(x) + p_{n-1} \delta_n(x) = \delta_{n+1}(p_n(x)) \in \text{Im}(\partial_{n+1})$$

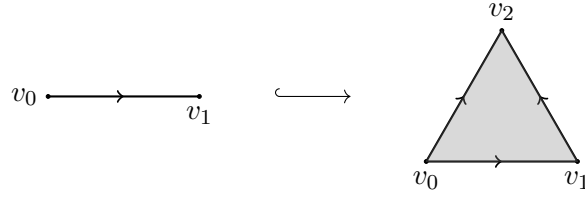
$$\Rightarrow (f_n - g_n)(x) \in \text{Im}(\partial_{n+1})$$

$$\left| \begin{array}{l} H_n(f)([x]) = [f_n(x)] \\ H_n(g)([x]) = [g_n(x)] \end{array} \right. \Rightarrow [f_n(x)] - [g_n(x)] = [f_n(x) - g_n(x)] = [\delta_{n+1} p_n(x)] = [0]$$

since $\delta_{n+1}(p_n(x)) \in \text{Im}(\partial_{n+1})$.

So, $[f_n(x)] = [g_n(x)] \Rightarrow H_n(f) = H_n(g) \quad \square$

Example 2.1.1. Let X be a 1 – simplex and Y a 2 – simplex:



$$C_{\bullet}(X, \partial) : \quad 0 \xrightarrow{\partial_2} \mathbb{Z} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_0=0} 0$$

$$D_{\bullet}(Y, \delta) : \quad \mathbb{Z} \xrightarrow{\delta_2} \mathbb{Z}^{\oplus 3} \xrightarrow{\delta_1} \mathbb{Z}^{\oplus 3} \xrightarrow{\delta_0=0} 0$$

Let's introduce maps on the chain complexes:

$$f_n : C_n(X, \partial) \rightarrow C'_n(Y, \delta)$$

$$g_n : C_n(X, \partial) \rightarrow C'_n(Y, \delta)$$

$$\begin{array}{ccccccc} 0 & \xrightarrow{\partial_2} & \mathbb{Z} & \xrightarrow{\partial_1 = \begin{bmatrix} -1 \\ 1 \end{bmatrix}} & \mathbb{Z}^{\oplus 2} & \xrightarrow{\partial_0=0} & 0 \\ & \searrow p_1=id & \downarrow f_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & & \downarrow g_1 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} & & \\ & & \mathbb{Z} & \xrightarrow{\delta_2 = \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}} & \mathbb{Z}^{\oplus 3} & \xrightarrow{\delta_1 = \begin{bmatrix} 0 & -1 & -1 \\ -1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}} & \mathbb{Z}^{\oplus 3} \xrightarrow{\delta_0=0} 0 \\ & & & \swarrow f_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} & & \swarrow g_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} & \end{array}$$

We can define $p_0 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$ and $p_1 = id_{\mathbb{Z}}$

For $n = 0$:

$$\begin{aligned} f_0 - g_0 &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \\ \delta_1 p_0 + 0 \circ \partial_0 &= \begin{bmatrix} 0 & -1 & -1 \\ -1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1 \\ 0 & 1 \end{bmatrix} \end{aligned}$$

For the choice of the maps p_0, f_0, g_0 : $f_0 \simeq g_0 \rightarrow$ homotopic equivalent

For $n = 1$:

$$\begin{aligned} f_1 - g_1 &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} - \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix} \\ \delta_2 p_1 + p_0 \circ \partial_1 &= \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} [1] + \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix} \end{aligned}$$

For the choice of the maps p_1, p_0, f_1, g_1 : $f_1 \simeq g_1 \rightarrow$ homotopic equivalent

By theorem 2.1.1, $H_0(f) = H_0(g)$ and $H_1(f) = H_1(g)$.

More precisely, $H_0(f) = H_0(g) = id_{\mathbb{Z}}$ and $H_1(f) = H_1(g) = 0$, since $H_0(X) = H_0(Y) = \mathbb{Z}$ and $H_n(X) = H_n(Y) = 0 \forall n > 0$

Lemma 2.1.1. A chain complex (C_\bullet, ∂) is contractible if id_C is homotopic equivalent to 0_C

If $id_C \simeq 0_C$, then $H_n(C_\bullet) = 0 \forall n$

Examples:

- $C_\bullet : \mathbb{Z} \xrightarrow{0} \mathbb{Z} \longrightarrow 0$
 $H_0(C_\bullet) = \mathbb{Z} = H_1(C_\bullet)$ implies that C_\bullet is not contractible
- $D_\bullet : \mathbb{Z} \xrightarrow{2} \mathbb{Z} \longrightarrow 0$
 $H_0(D_\bullet) = \mathbb{Z}/2\mathbb{Z}, H_1(D_\bullet) = 0$ implies that D_\bullet is not contractible
- $E_\bullet : \mathbb{Z} \xrightarrow{1} \mathbb{Z} \longrightarrow 0$
 $H_0(E_\bullet) = 0 = H_1(E_\bullet) \Rightarrow$ need to check that $id_E \simeq 0_E$

$$\begin{array}{ccccccc}
 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{\partial_1=1} & \mathbb{Z} & \xrightarrow{\partial_0=0} & 0 \\
 & & \downarrow id=0 & & \downarrow id=0 & & \\
 & \nearrow p_1 & & \nwarrow p_0 & & & \\
 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{\partial_1=1} & \mathbb{Z} & \xrightarrow{\partial_0=0} & 0
 \end{array}$$

We can assign $p_0 = id, p_1 = 0$.

For a cycle $\sigma \in E_1 = \mathbb{Z}$:

$(\partial_2 p_1 + p_0 \partial_1)(\sigma) = \partial_2 p_1(\sigma) + p_0 \partial_1(\sigma) = 0 + \sigma = \sigma = id - 0(\sigma) \Rightarrow id_E \simeq 0_E \Rightarrow (E_\bullet, \partial)$ is contractible

- $F_\bullet : \dots \xrightarrow{2} \mathbb{Z}/4 \xrightarrow{2} \mathbb{Z}/4 \xrightarrow{\partial=2} \mathbb{Z}/4 \xrightarrow{2} \mathbb{Z}/4 \xrightarrow{2} \dots$
 $\ker \partial = \text{Im } \partial = (2) \Rightarrow H_n(F_\bullet) = 0 \forall n \Rightarrow$ need to check that $id_F \simeq 0_F$

$$\begin{array}{ccccccc}
 \dots & \xrightarrow{2} & \mathbb{Z}/4 & \xrightarrow{2} & \mathbb{Z}/4 & \xrightarrow{2} & \dots \\
 & & \downarrow id=0 & & \downarrow id=0 & & \\
 & \nearrow p_1 & & \nwarrow p_0 & & & \\
 \dots & \xrightarrow{2} & \mathbb{Z}/4 & \xrightarrow{2} & \mathbb{Z}/4 & \xrightarrow{2} & \dots
 \end{array}$$

In $\mathbb{Z}/4$ we have four classes $\bar{0}, \bar{1}, \bar{2}, \bar{4}$. The boundary operator $\partial = \text{mult}(2)$ maps the four classes only in two maps $\bar{0}, \bar{2}$. So, the ∂ cannot be surjective.

For a cycle $\sigma \in \mathbb{Z}/4$:

Since $((2)p_1 + p_0(2))(\sigma) \in (2)$, $((2)p_1 + p_0(2))(\sigma) \neq \sigma \Rightarrow (F_\bullet, \partial)$ is not contractible

Theorem 2.1.2. Given topological spaces X, Y with maps $f : X \rightarrow Y$ and $g : Y \rightarrow X$
If

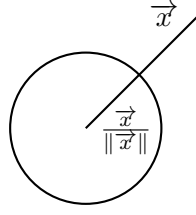
$$\begin{aligned}
 f \circ g &\simeq id_Y \\
 g \circ f &\simeq id_X
 \end{aligned}$$

where \simeq denotes homotopic equivalence, then

$$H_n(X) \xrightleftharpoons[g_*]{f_*} H_n(Y) \quad \forall n \in \mathbb{Z}$$

$H_n(X)$ is isomorphic to $H_n(Y)$, $\Rightarrow f_* = (g_*)^{-1}$ where f_*, g_* are the induced maps on homology.

Example 2.1.2. Let X be the n -dimensional sphere and Y the $(n+1)$ -dimensional real coordinate space without the origin, $X = S^n$ and $Y = \mathbb{R}^{n+1}/\{0\}$



$f : S^n \hookrightarrow \mathbb{R}^{n+1}/\{0\}$ is the usual inclusion

$$g : \mathbb{R}^{n+1}/\{0\} \rightarrow S^n \text{ s.t. } g(\vec{x}) = \frac{\vec{x}}{\|\vec{x}\|}$$

Clearly, $g \circ f \simeq id_S^n$ while $f \circ g : \vec{x} \mapsto \frac{\vec{x}}{\|\vec{x}\|} \neq id_{\mathbb{R}^{n+1}/\{0\}}$

Let's prove that $f \circ g$ is homotopic equivalent to $id_{\mathbb{R}^{n+1}/\{0\}}$: We can construct a function

$$\begin{aligned} F : [0, 1] \times \mathbb{R}^{n+1}/\{0\} &\longrightarrow \mathbb{R}^{n+1}/\{0\} \\ F(t, \vec{x}) &= (t(f \circ g) + (1-t)1_{\mathbb{R}^{n+1}/\{0\}}) \vec{x} \\ &= t\left(\frac{\vec{x}}{\|\vec{x}\|}\right) + (1-t)\vec{x} \end{aligned}$$

Clearly, $F(0, \vec{x}) = \vec{x} = id_{\mathbb{R}^{n+1}/\{0\}}$ and $F(1, \vec{x}) = \left(\frac{\vec{x}}{\|\vec{x}\|}\right) = f \circ g$.

So, $f \circ g \simeq id_{\mathbb{R}^{n+1}/\{0\}}$, and by theorem 2.1.2 $\Rightarrow f_* = (g_*)^{-1}$.

Example 2.1.3. Let X be a 1-simplex and Y a 0-simplex:

$$\begin{aligned} C_\bullet(X, \partial) : \quad & 0 \xrightarrow{\partial_2} \mathbb{Z} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 2} \xrightarrow{\partial_0=0} 0 \\ C'_\bullet(Y, \partial') : \quad & 0 \xrightarrow{0} 0 \xrightarrow{\partial'_1=0} \mathbb{Z} \xrightarrow{\partial'_0=0} 0 \end{aligned}$$

Let's introduce maps on the chain complexes:

$$\begin{aligned} f_n : C_n(X, \partial) &\rightarrow C'_n(Y, \partial') \\ g_n : C'_n(Y, \partial') &\rightarrow C_n(X, \partial) \end{aligned}$$

$$\begin{array}{ccccccc} 0 & \xrightarrow{\partial_2} & \mathbb{Z} & \xrightarrow{\partial_1} & \mathbb{Z}^{\oplus 2} & \xrightarrow{\partial_0=0} & 0 \\ & \searrow p_1 & \downarrow 0 & \swarrow p_0 & \uparrow [1 \atop 0] = g_0 & \downarrow f_0 = [1 \ 1] & \\ 0 & \xrightarrow{0} & 0 & \xrightarrow{\partial'_1=0} & \mathbb{Z} & \xrightarrow{\partial'_0=0} & 0 \end{array}$$

For $n = 0$:

$$\begin{aligned} f_0 \circ g_0 &= \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = id_{\mathbb{Z}} \\ g_0 \circ f_0 &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} \neq id_{\mathbb{Z}^{\oplus 2}} \end{aligned}$$

Let's prove that $g_0 \circ f_0$ is homotopic equivalent to $id_{\mathbb{Z}^{\oplus 2}}$:

For an arbitrary element $\begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{Z}^{\oplus 2}$:

$$(g_0 \circ f_0 - id_{\mathbb{Z}^{\oplus 2}}) \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = 0 \text{ and } (\partial'_1 p_0 + 0 \circ \partial_0) \begin{bmatrix} x \\ y \end{bmatrix} = 0 \implies g_0 \circ f_0 \simeq id_{\mathbb{Z}^{\oplus 2}}$$

To be continued and rechecked

2.2 Exact Sequences

Definition 2.2.1. A sequence of homomorphisms:

$$\dots \longrightarrow A_{n+1} \xrightarrow{\alpha_{n+1}} A_n \xrightarrow{\alpha_n} A_{n-1} \xrightarrow{\alpha_{n-1}} \dots$$

is exact if $\ker \alpha_n = \text{Im } \alpha_{n+1} \forall n$.

$\text{Im } \alpha_{n+1} \subseteq \ker \alpha_n$ is equivalent to $\alpha_n \alpha_{n+1} = 0$ since (A_\bullet, α) is a chain complex.
& $\ker \alpha_n \subset \text{Im } \alpha_{n+1} \Rightarrow H_n$ is trivial : $H_n = 0 \forall n$

Examples of short exact sequences:

1. $0 \rightarrow A \xrightarrow{\alpha} B$ is exact $\iff \ker \alpha = 0, \alpha$ is injective
2. $A \xrightarrow{\alpha} B \rightarrow 0$ is exact $\iff \text{Im } \alpha = B, \alpha$ is surjective
3. $0 \rightarrow A \xrightarrow{\alpha} B \rightarrow 0$ is exact $\iff \text{Im } \alpha = B$ and $\ker \alpha = \{0\}, \alpha$ is an isomorphism
4. $0 \rightarrow A \xrightarrow{\alpha} B \xrightarrow{\beta} C \rightarrow 0$ is exact \iff
 - (a) $\ker \alpha = \text{Im}(0 \rightarrow A) = 0 \Rightarrow \alpha$ is injective
 - (b) $\text{Im } \beta = C \Rightarrow \beta$ is surjective
 - (c) $\ker \beta = \text{Im } \alpha$

So, β induces an isomorphism $C \simeq \frac{B}{\text{Im } \alpha}$. C can be written as $C \simeq B/A$ if α is an inclusion of A as a subgroup of B .

Let us consider a short exact sequence of chain complexes:

$$0 \rightarrow A_\bullet \xrightarrow{i} B_\bullet \xrightarrow{\pi} C_\bullet \rightarrow 0$$

$A_\bullet, B_\bullet, C_\bullet$ are chain complexes and i, π are maps between chain complexes where $\ker \pi = \text{Im } i, \pi : \text{surjective and } i : \text{injective}$

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 A_\bullet : & \longrightarrow & A_n & \xrightarrow{\partial} & A_{n-1} & \xrightarrow{\partial} & A_{n-2} \longrightarrow \\
 & & \downarrow i_n & & \downarrow i_{n-1} & & \downarrow i_{n-2} \\
 B_\bullet : & \longrightarrow & B_n & \xrightarrow{\partial} & B_{n-1} & \xrightarrow{\partial} & B_{n-2} \longrightarrow \\
 & & \downarrow \pi_n & & \downarrow \pi_{n-1} & & \downarrow \pi_{n-2} \\
 C_\bullet : & \longrightarrow & C_n & \xrightarrow{\partial} & C_{n-1} & \xrightarrow{\partial} & C_{n-2} \longrightarrow \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

The induced sequence on homology:

$$H_n(A_\bullet) \xrightarrow{i_*} H_n(B_\bullet) \xrightarrow{\pi_*} H_n(C_\bullet) \forall n \quad (2.3)$$

$$\pi \circ i = 0 \Rightarrow \pi_* \circ i_* = 0, \quad H_n(\pi \circ i) = H_n(\pi) \circ H_n(i)$$

(2.3) need not be a short exact sequence. However, we can create a long exact sequence of

homology:

$$H_{n+1}(C_\bullet) \xrightarrow{\partial_{n+1}} H_n(A_\bullet) \xrightarrow{i_*} H_n(B_\bullet) \xrightarrow{\pi_*} H_n(C_\bullet) \xrightarrow{\delta} H_{n-1}(A_\bullet) \rightarrow H_{n-1}(B_\bullet) \rightarrow H_{n-1}(C_\bullet)$$

$$0 \rightarrow \text{Im } \delta_{n+1} \rightarrow H_n(A) \xrightarrow{i_*} H_n(B) \xrightarrow{\pi_*} H_n(C) \rightarrow \ker \delta_n \rightarrow 0$$

where the δ map is defined as:

$$\begin{aligned} \delta : H_n(C) &\rightarrow H_{n-1}(A) \\ [c] &\mapsto [a] \end{aligned}$$

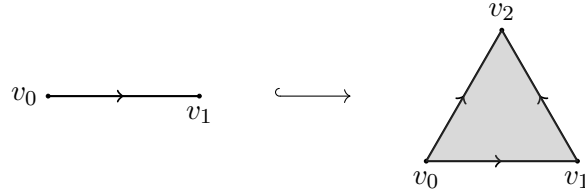
For a element $b \in B_n$ there exists $c = \pi_n(b)$ since π is onto.

If we apply the boundary map $\partial : B_n \rightarrow B_{n-1}$ on b , then $\partial b \in B_{n-1}$, $\pi_n(\partial b) = \partial(\pi_n(b)) = 0$

We can take an element $a \in A_{n-1}$ such that $i(a) = \partial(b)$

$\partial(\partial b) = \partial(i(a)) = i(\partial a) \Rightarrow \partial a = 0$ since i is injective $\Rightarrow \partial b = (0) \in A_{n-1}$

Example 2.2.1. Let consider X to be a 1 – simplex and Y a 2 – simplex



A short exact sequence of chain complexes for X, Y :

$$\begin{array}{ccccccc} & & 0 & & 0 & & \\ & & \downarrow & & \downarrow & & \\ A_\bullet : & 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{\partial = \begin{bmatrix} -1 \\ 1 \end{bmatrix}} & \mathbb{Z}^{\oplus 2} & \longrightarrow 0 \\ & & & \downarrow i_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & & \downarrow i_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} & \\ B_\bullet : & 0 & \longrightarrow & \mathbb{Z}^{\oplus 3} & \xrightarrow{\partial = \begin{bmatrix} 0 & -1 & -1 \\ -1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}} & \mathbb{Z}^{\oplus 3} & \longrightarrow 0 \\ & & & \downarrow \pi_1 & & \downarrow \pi_0 & \\ C_\bullet : & 0 & \longrightarrow & C_1 & \longrightarrow & C_0 & \longrightarrow 0 \\ & & & \downarrow & & \downarrow & \\ & & & 0 & & 0 & \end{array}$$

The short exact sequence of complexes induces a long exact sequence on homology:

$$0 \rightarrow H_1(A) \rightarrow H_1(B) \rightarrow H_1(C) \xrightarrow{\delta} H_0(A) \rightarrow H_0(B) \rightarrow H_0(C) \rightarrow 0$$

Explicitly, the long exact sequence is:

$$0 \rightarrow 0 \rightarrow \mathbb{Z} \rightarrow H_1(C) \xrightarrow{\delta} \mathbb{Z} \xrightarrow{1} \mathbb{Z} \xrightarrow{\alpha} H_0(C) \rightarrow 0$$

$$\ker(1) = \{0\} = \text{Im } \delta$$

$$\ker(\alpha) = \text{Im}(1) = \mathbb{Z}$$

$$C_1 = \mathbb{Z}^{\oplus 3} / \text{Im } i_1 \simeq \mathbb{Z}^{\oplus 2}$$

$$C_0 = \mathbb{Z}^{\oplus 3} / \text{Im } i_0 \simeq \mathbb{Z}$$

The boundary operator between C_1, C_0 :

$$\partial : C_1 \rightarrow C_0$$

$$\partial : \begin{bmatrix} a \\ b \end{bmatrix} \mapsto (a + b)$$

$$\begin{bmatrix} a \\ b \\ 0 \end{bmatrix} = \begin{bmatrix} a \\ b \\ 0 \end{bmatrix} \text{mod}(\text{Im } i_1) \xrightarrow{\partial = \begin{bmatrix} 0 & -1 & -1 \\ -1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}} \begin{bmatrix} -b \\ -a \\ a + b \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ a + b \end{bmatrix}$$

$$H_1(C) = \left\{ \begin{bmatrix} a \\ -a \end{bmatrix} \right\} \simeq \mathbb{Z}$$

$$H_0(C) = C_0 / C_0 = 0$$

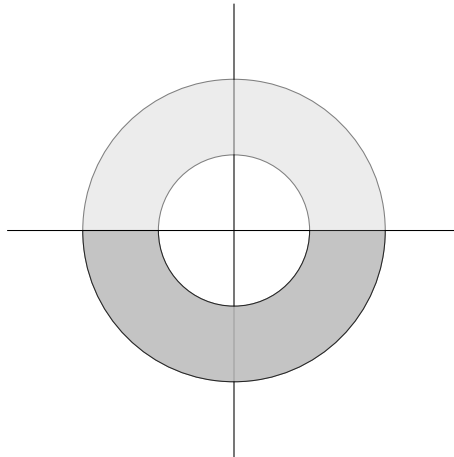
Let us take an example when $Y \subseteq X$ subspace, the short exact sequence of chain complexes is:

$$0 \rightarrow C_n(Y) \rightarrow C_n(X) \rightarrow C_n(X)/C_n(Y) \rightarrow 0$$

We get a long exact sequence on homology:

$$H_n(Y) \rightarrow H_n(X) \rightarrow H_n(X, Y) \xrightarrow{\delta} H_{n-1}(Y) \rightarrow H_{n-1}(X) \rightarrow \dots$$

Example 2.2.2. Consider X to be the annulus, and the shaded area $Y \subseteq X$



$$\begin{aligned}
X &= \{(x, y) | 1 \leq x^2 + y^2 \leq 2\} \\
Y &= \{(x, y) | 1 \leq x^2 + y^2 \leq 2, y \leq 0\} \\
\delta &: H_1(X, Y) \rightarrow H_0(Y) \\
\delta([\sigma]) &= [\partial\sigma] = [\sigma(1) - \sigma(0)]
\end{aligned}$$

In "good cases" $H_n(X, Y) = H_n(X/Y)$

For two topological spaces $Y \subseteq X$ "pairs of spaces".

We can construct the following chain complex:

$$0 \rightarrow C_n(Y) \xrightarrow{i} C_n(X) \xrightarrow{\pi} C_n(X)/C_n(Y) \rightarrow 0, \quad C_n(X, Y) \text{ are relative chains}$$

Elements of C_n : $\sigma : \Delta^n \rightarrow Y \subseteq X$

$$\begin{aligned}
\partial : C_n(X, Y) &\rightarrow C_{n-1}(X, Y) \\
\delta \pmod{C_n(Y)} &\mapsto \partial\delta \pmod{C_{n-1}(Y)} \\
H_n(X, Y) &\equiv H_n(C_\bullet(X, Y)) = Z_n(X, Y)/B_n(X, Y), \quad \text{cycle/boundary}
\end{aligned}$$

Definition 2.2.2 (Retraction). Consider $Y \subseteq X$, a retraction of X onto Y is a map $r : X \rightarrow Y$ such that, $r(X) = Y$ and $r^2 = r$.

i.e. $r(y) = y$ if $y \in Y$
 $i : Y \rightarrow X \quad r \circ i = id_Y \quad i \circ r \neq id_X$ but $r_* \circ i_* = id$ in homology

Definition 2.2.3 (Deformation retract). Consider $Y \subseteq X$: subspace
 Y is a deformation retract of X if there is a homotopy between id_X and a retraction $r : X \rightarrow Y$

$$(F_t) \quad \left. \begin{array}{l} F_t : X \rightarrow X \quad F_0 : id_X \\ F_1 : X \rightarrow Y \quad F_1|_Y = id_Y \\ F_1(X) = Y \end{array} \right| F_0 \simeq F_1 \text{ homotopic, } id_X \simeq r$$

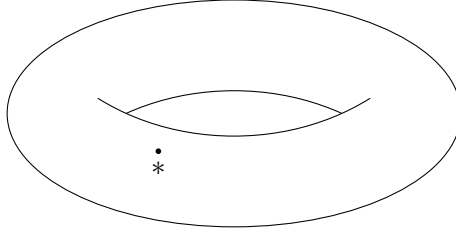
(X, Y) is a "good pair" if

- $Y \subseteq X$ - closed
- There is open $V \subseteq X$, such that V is a deformation retracts on Y .

Example 2.2.3.

(\mathbb{R}^{n+1}, S^n) is a good pair
 $S^n \subseteq \mathbb{R}^{n+1}$ - closed
 $S^n \subseteq (\mathbb{R}^{n+1}/\{0\})$ and is a deformation retracted of it

Example 2.2.4. Consider X to be a torus, and Y a point on its surface:



$$Y = \{*\}_{pt} \hookrightarrow X$$

$$0 \rightarrow C_n(Y) \rightarrow C_n(X) \rightarrow C_n(X/*) \rightarrow 0$$

$$H_n(Y) = \begin{cases} 0 & n \neq 0 \\ \mathbb{Z} & n = 0 \end{cases}$$

$$\cdots \rightarrow H_n(Y) \rightarrow H_n(X) \rightarrow H_n(X, *) \rightarrow H_{n-1}(Y) \rightarrow \cdots$$

$$\cdots \rightarrow H_0(Y) \rightarrow H_0(X) \rightarrow H_0(X, *) \rightarrow 0$$

$$n > 0: \quad H_n(X, *) = H_n(X)$$

$$n = 0: \quad 0 \rightarrow \mathbb{Z} \rightarrow H_0(X) \rightarrow H_0(X, *) \rightarrow 0$$

$$H_0(X, *) = H_0(X)/\mathbb{Z}, \quad i.e. \quad \begin{matrix} H_0(X) = \mathbb{Z}^d \\ H_0(X) = \mathbb{Z}^{d-1} \end{matrix}$$

Remark: Sometimes one introduces “reduced homology”

$$\cdots \rightarrow C_n(X) \rightarrow C_{n-1} \rightarrow \cdots \xrightarrow{\partial_1} C_0(X) \xrightarrow{\epsilon} \mathbb{Z} \rightarrow 0, \quad \tilde{H}_n(X) - \text{reduced homology}$$

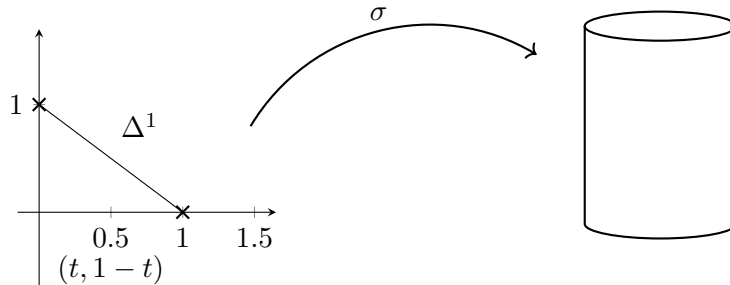
$$\sum n_i \sigma_i \mapsto \sum_i n_i \in C_0(X)$$

$$\tilde{H}_n(X) = \begin{cases} H_n(X), & n > 0 \\ H_0^{sing}(X) = H_0(X) \oplus \mathbb{Z} & n = 0 \end{cases}$$

$$H_n(X, *) \rightarrow \tilde{H}_n(X)$$

Let us consider some examples of Reduced Homology:

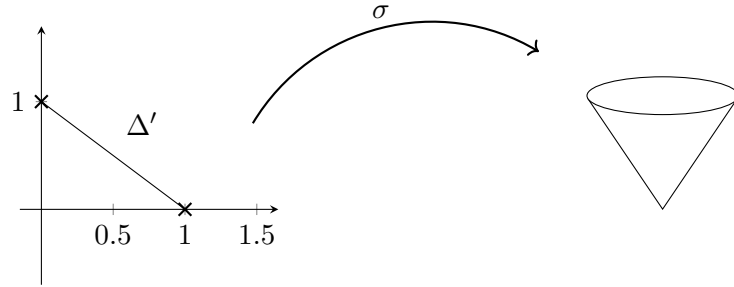
Example 2.2.5. Consider $X = S^1 \times [0, 1]$, and $Y = S^1 \times \{0\}$:



$$\sigma : \Delta^1 \mapsto S^1 \times [0, 1]$$

$$\sigma : t \mapsto (\cos 2\pi t, \sin 2\pi t, 1)$$

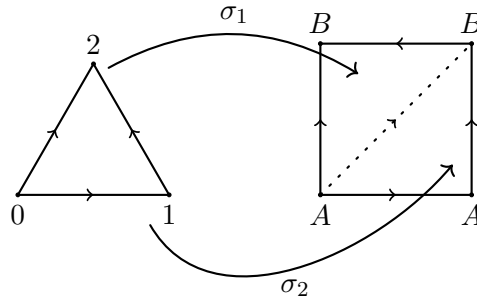
The boundary operator on σ : $\partial\sigma = 0 \rightsquigarrow [\sigma] \in H_1(X)$
The space X is homotopic equivalent to S^1 so, $H_1(X) \simeq H_1(S^1) \simeq \mathbb{Z}$, considered in 2.1.
Let us take the quotient map X/Y . The space Y will contract into a point creating a cone.



In $H_1(X, Y)$ the class $[\sigma] \in H_1(X)$ goes to 0 and the long exact sequence on homology is:

$$H_1(Y) \rightarrow H_1(X) \rightarrow H_1(X, Y) \rightarrow H_0(X, Y) \rightarrow H_0(Y) \rightarrow H_0(X) \rightarrow 0$$

where $H_1(Y), H_1(X), H_0(Y), H_0(X) \simeq \mathbb{Z}$.



$$\partial\sigma_1 = \sigma_1|_{[12]} - \sigma_1|_{[02]} + \sigma_1|_{[01]}$$

$$\partial\sigma_2 = \sigma_2|_{[12]} - \sigma_2|_{[02]} + \sigma_2|_{[01]}$$

$$\partial(\sigma_1 + \sigma_2) = \sigma_1|_{[12]} + \sigma_2|_{[01]}$$

We can choose $\sigma = \sigma_1|_{[12]} = \partial(\sigma_1 + \sigma_2) - \sigma_2|_{[01]}$, $\sigma_2|_{[01]} \in C_1(Y)$
 $\sigma \in B_1(X, Y) \Rightarrow [\sigma] = 0 \in H_1(X, Y)$

Chapter 3

Persistent Homology

Persistent homology (PH) is a method used in topological data analysis (TDA) to study qualitative features of data that persist across multiple scales. Due to its construction, persistent homology computations are robust to perturbation of the data. Also, PH is used to extract relevant features of the data, and separate them from noise.

An important result in computing persistent homology is that the persistent homology of a filtered d -dimensional simplicial complex is simply the standard homology of a particular graded module over a polynomial ring [ZC05].

Before introducing Persistent homology and understanding its calculation, we need to provide some preliminary concept from algebra.

We begin by reviewing graded modules and rings and then stating the structure of finitely generated modules over principal ideal domains. Then, referring to the notions introduced in Chapter 1, we provide some comments of the reduction algorithm used for computing simplicial homology. We conclude this chapter by describing persistent homology.

3.1 Background

3.1.1 Graded Rings and Modules

A graded ring is a ring $\langle R, +, \cdot \rangle$ equipped with a direct sum decomposition of Abelian groups $R \cong \bigoplus_{i \in \mathbb{Z}} R_i$, so multiplication is defined by bilinear pairings $R_n \otimes R_m \rightarrow R_{n+m}$.

Elements in a single R_i are called homogeneous and have degree i , $\deg e = i$ for all $e \in R_i$.

Example 3.1.1. $R = A[t]$, where $(A - \text{commutative ring})$

$$R_0 = A, \quad R_1 = \{at, a \in A\}, \quad \dots, \quad R_i = \{at^i, a \in A\}$$

Example 3.1.2. $R = \mathbb{R}[x, y, z]$

$$R_i = \{cx^{d_1}y^{d_2}z^{d_3} \mid \sum_{k=1}^3 d_k = i\}$$

For example $R_1 \simeq \mathbb{R}^3$ as a vector space $\{ax + by + cz\}$

A graded module M over a graded ring R is a module equipped with a direct sum decomposition $M \cong \bigoplus_{i \in \mathbb{Z}} M_i$, so that the action of R on M is defined by bilinear pairings $R_n \otimes M_m \rightarrow M_{n+m}$.

A graded ring (module) is non-negatively graded if $R_i = 0$ ($M_i = 0$) for all $i < 0$.

Note: R is a PID if it's a domain (no zero divisors) & all its ideal are principal

For example:

$$\begin{aligned} R &= \mathbb{Z}, \quad I = (n), \quad n \in \mathbb{Z} \\ R &= k[t], \quad k = \text{field} \end{aligned}$$

The structure theorem describes finitely generated modules and graded modules over PIDs.

Theorem 3.1.1 (Structure Theorem). *If D is a PID, then every finitely generated D -module is isomorphic to a direct sum of cyclic D -module. That is, it decomposes uniquely into the form*

$$D^\beta \oplus (\oplus_i D/d_i D), \quad (3.1)$$

for $d_i \in D$, $\beta \in \mathbb{Z}$, such that $d_i | d_{i+1}$. Similarly, every graded module M over a graded PID D decomposes uniquely into the form

$$(\oplus_i \Sigma^{\alpha_i} D) \oplus (\oplus_i \Sigma^{\gamma_i} D/d_i D), \quad (3.2)$$

where $d_j \in D$ are homogeneous elements so that $d_j | d_{j+1}$, $\alpha_i, \gamma_j \in \mathbb{Z}$, and Σ^α denotes an α -shift upward in grading.

The free portion on the left is a vector includes generators that may generate an infinite number of elements. Decomposition (3.1) has a vector space of dimension β . The torsional portion on the right includes generators that may generate a finite number of elements. These torsional elements are also homogeneous. Intuitively then, the theorem describes finitely generated modules and graded modules as structures that look like vector spaces but also have some dimensions that are "finite" in size.

Example 3.1.3. Let us take $D = k[t]$ – graded ring (e.g. $\mathbb{R}[t]$) then:

$$\begin{array}{ccccccc} D & = & k & \oplus & kt & \oplus & kt^2 \oplus \dots \\ & & \parallel & & \parallel & & \parallel \\ & & M_0 & & M_1 & & M_2 \end{array}$$

is also a graded module over itself.

$$\begin{aligned} M &= \sum_{\alpha} D = t^\alpha k[t] \subseteq k[t] \text{ is an ideal of } D \Rightarrow D\text{-module} \\ M &= M_\alpha \oplus M_{\alpha+1} \oplus \dots \\ &\quad \begin{array}{cc} \wr & \wr \\ k & kt \end{array} \\ (\sum_{\alpha} D)_i &= D_{\alpha+i} \end{aligned}$$

3.1.2 Reduction

The reduction algorithm is the standard method used in computing homology. For simplicity, we describe the method for integer coefficients. However, the method applies also to modules over arbitrary PIDs.

Given C_k , we can use as standard basis the oriented k-simplices:

$$\begin{aligned} \partial_k : C_k &\rightarrow C_{k-1} \\ \{e_i\} &\quad \{e_i\} \\ (C_k, C_{k-1} : \text{free abelian groups or free R-module}) \\ M_k : \text{standard matrix representation of } \partial_k \\ e \cdot u : (e_1, \dots, e_{m_k}) &\begin{pmatrix} u_1 \\ \vdots \\ u_{m_k} \end{pmatrix} \in C_k \\ \partial_k(eu) &= \hat{e}(M_u) \end{aligned}$$

The null-space of M_k corresponds to Z_k and its range-space to B_{k+1} . The reduction algorithm derives alternate bases for the chain groups, relative to which the matrix for ∂_k is diagonal. The algorithm utilizes the following elementary column operations on M_k :

- exchange column i, and column j,
- multiply column i by -1
- replace column i by (column i) + q(column j), where $q \in \mathbb{Z}$ and $i \neq j$

The algorithm also uses elementary row operation that are similarly defined. The idea of the reduction algorithm is to systematically modify the bases of C_k and C_{k+1} using elementary operations so that it reduce M_k to its Smith normal form:

Row-operation

$$\begin{aligned} R_i &\mapsto R_i + qR_j \text{ on } M \\ M &\mapsto i \underbrace{\begin{pmatrix} 1 & & & & \\ & \ddots & & & \\ & & 1 & \cdots & q \\ & & & \ddots & \\ & & & & 1 \end{pmatrix}}_A M \\ R_2 &\mapsto R_2 + 2R_3 \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{pmatrix} M \\ (e_1 \ e_2 \ e_3) &\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{pmatrix} \mapsto (e_1 \ e_2 \ 2e_2 + e_3) \end{aligned}$$

Column operations:

$$M \mapsto MB, B_2 \begin{pmatrix} 1 & & & \\ & \ddots & & \\ & & 1 & \\ & & \vdots & \ddots \\ & & q & & 1 \end{pmatrix}$$

Interpretation of row/column operations on a matrix of a map in terms of changing bases.

$$\partial : \xi = \underline{e}u \mapsto \hat{e}Mu \text{ where } u = [\xi]_{\underline{e}}$$

Suppose we perform a column-operation $M \mapsto MB$. This is supposed to change the matrix of a map - keeping the map unchanged

$$\begin{aligned} \xi &= \underline{e}u \mapsto \hat{e}Mu = \hat{e}MB(B^{-1}u) \\ &\parallel \\ &\underline{e}B(B^{-1}u) \end{aligned}$$

$$\text{If we set } \underline{e}' = \underline{e}B$$

$$\partial : \xi = \underline{e}'v \mapsto \hat{e}MBv$$

$$v = [\xi]_{\underline{e}'}$$

Similarly, suppose we perform a row-operation $M \mapsto AM$. Then

$$\begin{aligned} \xi = \underline{e}u \mapsto \underline{\hat{e}}Mu &= \underline{\hat{e}}A^{-1}AMu \\ &= \underline{\hat{e}}'AMu \end{aligned}$$

That is, if $M = [\partial]_{\underline{e}\hat{e}}$, then

$$AMB = [\partial]_{\underline{e}B, \underline{\hat{e}}A^{-1}}$$

$$A = I + qE_{ij} : R_i \mapsto R_i + qR_j \text{ (via } M \mapsto AM)$$

$$A^{-1} = I - qE_{ij}$$

$$\begin{aligned} \underline{\hat{e}}A^{-1} &= (\hat{e}_1, \dots, \hat{e}_{m_{k-1}}) \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & \ddots & \dots & q \\ & & & 1 & \\ & & & & 1 \end{pmatrix}^i = \\ &= (\hat{e}_1, \dots, \hat{e}_j - q\hat{e}_i, \dots), \text{ i.e. } \hat{e}_j \mapsto \hat{e}_j - q\hat{e}_i \end{aligned}$$

$$B = I + qE_{ji} : C_i \mapsto C_i + qC_j \text{ (via } M \mapsto MB)$$

$$\underline{e}B = (e_1, \dots, e_{m_k}) \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & & \ddots & \dots & q \\ & & & 1 & \\ & & & & 1 \end{pmatrix}^j = (e_1, \dots, e_i + qe_j, \dots)$$

Let $V \simeq \mathbb{R}^n$ (be a vector space)

$$B = \{e_1, \dots, e_n\}$$

$$V = \underline{e}X = (e_1, \dots, e_n) \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} = \sum_{i=1}^n x_i e_i \quad (e_i \in V, x_i \in \mathbb{R})$$

$$B^1 = \{f_1, \dots, f_n\}$$

$$v = \underline{e}X = \underbrace{\underline{e}}_{\mathbf{f}} T^{-1} \underbrace{(TX)}_Y = (f_1, \dots, f_n)Y$$

$$(f_1, \dots, f_n) = (l_1, \dots, l_n)T^{-1}$$

$$Y = TX$$

Smith normal form (for PID):

$$\exists A, B :$$

$$\partial_k \equiv AMB = \left(\left(\begin{array}{ccc|c} b_1 & & & \overbrace{0}^{b_i|b_{ix1}} \\ & \ddots & & \\ & & b_l & \\ \hline & & & 0 \end{array} \right) \right)$$

$$\text{rank } Z_k = m_k - e_k$$

$$\text{rank } H_k = m_k - e_k - e_{k+1}$$

3.2 The Persistence Module

In this section we will combine the homology of all the complexes in the filtration into a single algebraic structure. We then establish a correspondence that reveals a simple description over fields. Most significantly, we illustrate that the persistent homology of a filtered complex is simply the standard homology of a particular graded module over a polynomial ring.

Taking into consideration the construction of a filtered simplicial complex introduced in section 1.2, we can construct a filtered chain complex:

$$\begin{array}{ccc} (0) \subseteq C_\bullet^1 \subseteq C_\bullet^2 \subseteq \dots \subseteq C_\bullet^m \\ \parallel & & \parallel \\ C_\bullet^0 & & C_\bullet \end{array}$$

Definition 3.2.1. (*Persistent Homology Group*). Given a filtered complex, the i -th complex K^i has associated boundary operators ∂_k^i , matrices M_k^i , and groups C_k^i , Z_k^i , B_k^i , and H_k^i for all $i, k \geq 0$. The p -persistent k -th homology group of K^i is

$$H_k^{i,p} = Z_k^i / (B_k^{i+p} \cap Z_k^i)$$

For $p = 0$, this is the usual homology formula:

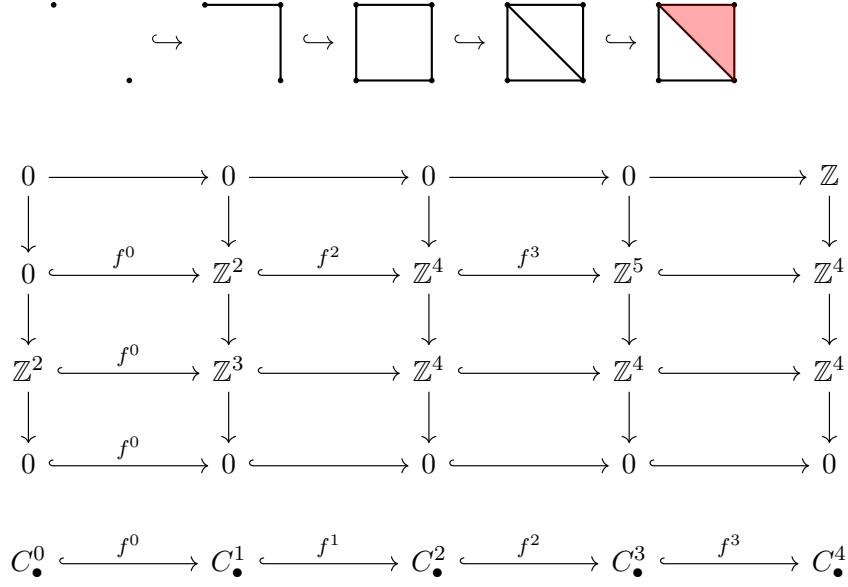
$$H_k(C_\bullet^i) = Z_k^i / (B_k^i \cap Z_k^i) = Z_k^i / B_k^i$$

Definition 3.2.2. (*Persistence Complex*)

A persistence complex \mathcal{C} is a family of chain complexes $\{C_*^i\}_{i \geq 0}$ over R , together with a chain map's $f_i : C_*^i \rightarrow C_*^{i+1}$ so that we have the following diagram:

$$C_*^0 \xrightarrow{f^0} C_*^1 \xrightarrow{f^1} C_*^2 \xrightarrow{f^2} \dots$$

Example 3.2.1. Let us consider the following filtered simplicial complex, and the filtered chain complex:



Definition 3.2.3. (*Persistence Module*). A persistence module \mathcal{M} is a family of R -modules, M^i , together with homomorphism $\varphi^i : M^i \rightarrow M^{i+1}$

Suppose we have a persistence module $\mathcal{M} = \{M^i, \varphi^i : M^i \rightarrow M^{i+1}\}$ over a ring R , We can equip $R[t]$ with the standard grading and define a graded module over $R[t]$ by

$$\alpha(M) = \bigoplus_{i \geq 0} M_i$$

, where the R -module structure is the sum of the structures on the individual components, and where the action of t is given by:

$$t \cdot (m^0, m^1, \dots) = (0, \varphi^0(m^0), \varphi^1(m^1), \dots)$$

$$\begin{pmatrix}
0 & | & & | \\
\hline
\varphi^0 & 0 & & \\
\hline
& \varphi^1 & 0 & \\
\hline
& & \varphi^2 & \\
\hline
\end{pmatrix}$$

t simply shift elements of the module up in gradation.

Example 3.2.2.

$$\begin{aligned}
& \varphi : \mathbb{R}^n \rightarrow \mathbb{R} \\
& \varphi : \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \mapsto (A_1, \dots, A_n) \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} = A_1 x_1 + \dots + A_n x_n \\
& (\varphi_1, \dots, \varphi_{n-1}) \mathbb{R}^n \rightarrow \mathbb{R}^{n-1} \\
& \underline{x} \mapsto \begin{pmatrix} A_{11} & \dots & A_{m-1} \\ \dots & \dots & \dots \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \\
& \text{e.g. } \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} x \\ y \end{pmatrix}
\end{aligned}$$

Theorem 3.2.1. (*Correspondence*) *The correspondence α defines an equivalence of categories between the category of persistence modules of finite type over R and the category of finitely generated non-negatively graded modules over $R[t]$.*

The Correspondence theorem gives us a simple decomposition when the ground ring is a field F . In this case the graded ring $F[t]$ is a PID and its only graded ideals are homogeneous of form (t_n) , so the structure of the $F[t]$ – module is described by sum (3.2) in structure theorem 3.1.1:

$$(\oplus_i \Sigma^{\alpha_i} F[t]) \oplus (\oplus_j \Sigma^{\gamma_j} F[t]/(t^{n_j})). \quad (3.3)$$

3.3 Čech and Vietoris-Rips Complex

In a ever-increasing world of data, the need for data analysis techniques and method is very high. Topological Data Analysis is a relatively new sphere in Data Analysis, that is bringing new insights in the study of data.

The principal themes is previous surveys from Carlsson, de Silva, Harer, Zomorodian and other, are:

1. It is useful to replace a set of data points with a family of simplicial complexes, indexed by a proximity parameter.
2. It is beneficial to use persistent homology to calculate these topological complexes.
3. It is helpful to encode the persistent homology of a data set in the form of a parameterized version of a Betti number: a barcode

Data is collected from different number of sources, and comes in a variety of form and shapes. Often data is represented as a unordered sequence of points in a Euclidean n – *dimensional* space \mathbb{E}^n . The overall shape of data might provide important information about the underlying phenomena that the data represents. A **point cloud data** is the type of dataset where global feature are present and important. It is exactly this type of data that is tackled by persistent homology.

Naturally, the question of how to represent a collection of points $\{x_\alpha\}$, rises. A straightforward approach would be to use the point cloud as vertices of a combinatorial graph whose edges

are determined by proximity, for example within a specific distance ϵ . A graph of this type can capture the connection of the point cloud, but it will fail to detect any higher order features beyond clustering. A good way to tackle this issue, is to complete the graph to a simplicial complex. The choice of how to fill in the higher dimensional simplices of the proximity graph will result in different global representations.

Two more prominent ways on how to fill in the higher dimensional simplices are: Čech and Vietoris-Rips Complex:

Definition 3.3.1. (*Čech Complex*) Given a collection of points $\{x_\alpha\}$ in Euclidean space \mathbb{E}^n , the Čech Complex, \mathcal{C}_ϵ , is the abstract simplicial complex whose k -simplices are determined by unordered $(k+1)$ -uple of points $\{x_\alpha\}_0^k$ whose closed $\epsilon/2$ - ball neighborhoods have a point of common intersection.

Definition 3.3.2. (*Vietoris-Rips Complex*) Given a collection of points $\{x_\alpha\}$ in Euclidean space \mathbb{E}^n , the Rips Complex, \mathcal{R}_ϵ , is the abstract simplicial complex whose k -simplices correspond to unordered $(k+1)$ -uple of points $\{x_\alpha\}_0^k$ which are pairwise within distance ϵ .

Chapter 4

Computing Persistent Homology

So far we have build the following setup to compute persistence homology on persistence chain complex:

$$\text{Persistence complex} : C_{\bullet}^0 \hookrightarrow C_{\bullet}^1 \hookrightarrow C_{\bullet}^2 \hookrightarrow \dots$$

$$\text{Persistent Homology Group} : H_k^{i,p} = Z_k^i / B_k^{i+p} \cap Z_k^i$$

$$\text{where } Z_k^i = \ker(\partial_k^i : C_k^i \rightarrow C_{k-1}^i) = \text{Im}((H_k^i = H_k(C_{\bullet}^i) \rightarrow (H_k(C_{\bullet}^{i+p})))$$

Example 4.0.1. Consider X to be a space consisting of two points and Y , of an edge. Then we can construct the following persistence complex:

$$\bullet \quad \bullet \quad \text{---} \bullet$$

$$C_{\bullet}^0 \xrightarrow{f_0} C_{\bullet}^1$$

$$\begin{array}{ccc} 1 & (0) & \xrightarrow{\quad} \mathbb{Z} \\ \partial_1=0 \downarrow & & \downarrow \partial_1 = \begin{bmatrix} -1 \\ 1 \end{bmatrix} \\ 0 & \mathbb{Z}^2 & \xrightarrow{\quad} \mathbb{Z}^2 \\ \partial_0=0 \downarrow & & \downarrow \partial_0 = \begin{bmatrix} 0 & 0 \end{bmatrix} \\ & 0 & \xrightarrow{\quad} 0 \end{array}$$

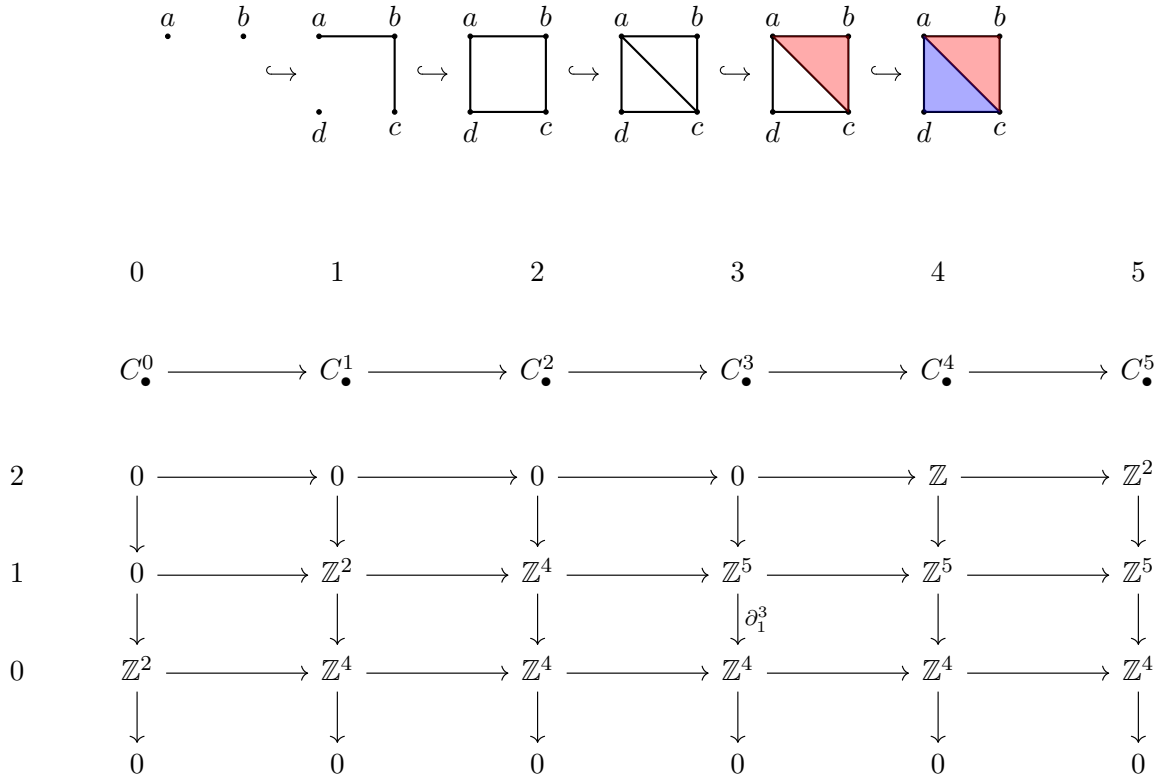
$$\underline{p=0}$$

$$\begin{aligned} H_k^{i,0} &= Z_k^i / B_k^i \cap Z_k^i \\ H_1^{0,0} &= (0) \quad H_1^{1,0} = (0) \\ H_0^{0,0} &= \mathbb{Z}^2 \quad H_0^{1,0} \simeq \mathbb{Z} \end{aligned}$$

$p = 1$

$$\begin{aligned}
H_k^{i,1} &= Z_k^i / B_k^{i+1} \cap Z_k^i \\
H_1^{0,1} &= Z_0^1 / B_1^1 \cap Z_1^0 = (0) \quad H_1^{1,1} = (0) \\
H_0^{0,1} &= Z_0^0 / B_0^1 \cap Z_0^0 = \mathbb{Z}^2 / \text{Im} \begin{bmatrix} -1 \\ 1 \end{bmatrix} \simeq \mathbb{Z}
\end{aligned}$$

Example 4.0.2. Let us consider the following filtered complex:



Some explicit computations are:

Here the matrix of ∂_1^3 is

$$\left(\begin{array}{c|ccccc} & ab & bc & cd & ad & ac \\ \hline d & 0 & 0 & 1 & 1 & 0 \\ c & 0 & 1 & -1 & 0 & 1 \\ b & 1 & -1 & 0 & 0 & 0 \\ a & -1 & 0 & 0 & -1 & -1 \end{array} \right) = M_1$$

Introduce the structure of a graded module over $k[t]$ (on $R[t]$)
Degrees \iff appearance in the translation

- $a, b\}$ deg 0

- $\left. \begin{matrix} c, d \\ ab, bc \end{matrix} \right\} \text{ deg } 1$
- $ab, dc \text{ deg } 2$
- $ac \text{ deg } 3$
- $abc \text{ deg } 4$
- $adc \text{ deg } 5$

If we work in $(\mathbb{Z}/2\mathbb{Z})[t]$

$$M_1 = \left(\begin{array}{c|ccccc} & ab & bc & cd & ad & ac \\ \hline d & 0 & 0 & t & t & 0 \\ c & 0 & 1 & t & 0 & t^2 \\ b & t & t & 0 & 0 & 0 \\ a & t & 0 & 0 & t^2 & t^3 \end{array} \right)$$

Remarks:

* Any ideal $\omega \subseteq R$ in a commutative ring in as R - module in a natural way: $\forall a \in \omega, \forall r \in R, r \cdot a \in \omega$ and $\omega \subseteq R$ is an abgroup (R is a module over itself & ω is a submodule)

* Hence for any

$$\begin{array}{ccc} & n \in \mathbb{N} & \\ & (t^n) & \subseteq k[t] \\ & \parallel & \\ \{ t^n & P(t), P \in k[t] \} & \\ & \parallel & \\ t^n k[t] & & \end{array}$$

is a $k[t]$ - module. This is a free $k[t]$ - module.

* $R = k[t]$ has a natural structure of graded ring. The $\text{deg } i$ - elements are the (non-zero) elements of the line $R_i := kt^i \subseteq k[t]$ (in general: $R = \oplus R_i, R_i R_j \subseteq R_{i+j}$). The ideal $(t^n) \subseteq k[t]$ is then a graded $k[t]$ - module (in general, this means $M = \oplus_i M_j, R = \oplus_i R_i, R_i \cdot M_j \subseteq M_{i+j}$)

$$(t^n) = t^n, k[t] = \bigoplus_{i \geq 0} \underbrace{kt^{n+i}}_{(t^n)}$$

i.e.

degree - i elements of (t^n) are the monomials of degree $(n + i)$

* While $(t^n) \subseteq k[t]$ is an ideal, so $k[t]$ - module - and so $k[t]$ - submodule; and a graded $k[t]$ - module, it is not a graded $k[t]$ - submodule!

The grading of (t^n) is not the grading that is induced by the ambient $k[t]$: it is shifted up by n : t^{n+i} , as an alternative of $(t^n) = t^n k[t]$, has degree i , not degree $(n + i)$.

* In general, for a graded module M over a graded ring R we can define the twist of M by n , $M[n]$, also denoted by $\sum^n M$, is defined by $(\sum^n M)_i = M_{n+i}$.

i.e., by redefining/shifting the grading up by n . We see that we can identify $\sum^n k[t]$ with $(t^n) = t^n k[t]$ as graded modules $(\sum^n k[t])_i = k[t]_{n+i} = kt^{n+i} \xrightarrow{id} kt^n \cdot t^i$

* A map of free $k[t]$ - modules $k[t] \rightarrow k[t]$ is multiplication by some polynomial $p(t)$ ie of the kind $p(t) \mapsto p(t)q(t)$ ($p(t)$ is the image of $1 \in k[k]$). More generally, a map of free $k[t]$ - module, $k[t]^{\oplus m} \rightarrow k[t]^{\oplus r}$ is given by some $r \times m$ matrix with $k[t]$ - entries.

* A map (morphism) if graded R-modules $\varphi : M \rightarrow N$ is a map of R - modules (ie: R - linear, ie: $\varphi(rm) = r\varphi(m), \varphi(m_1 + m_2) = \varphi(m_1) + \varphi(m_2)$) which preserves the degrees. That is $\varphi(M_i) \subseteq N_i, \forall i$.

* In particular, a map of graded modules $\varphi : \sum^n k[t] \rightarrow \sum^p k[t]$ must send $(t^n)_i = kt^{n+i}$ to

$$\begin{array}{ccc} \downarrow & & \downarrow \\ (t^n) & & (t^p) \end{array}$$

$$(t^p)_i = kt^{p+i}.$$

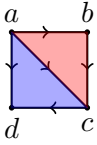
* As the shifts $\sum^n k[t]$ are still free modules, any $k[t]$ - module homomorphism $\varphi : (t^n) \rightarrow (t^p)$ is determined by some polynomial $p(t) \in k[t]$, ie by the image of a generator: $\varphi(t^n) = p(t)t^p$ as $\varphi(t^n q(t)) = q(t)\varphi(t^n)$. However if φ is a graded module homomorphism, we must have that $\varphi(t^n) = \underbrace{(mt^p)}_{p(t)} t^p$, ie, that $p(t)$ be homogeneous. Similarly, for direct sums $\bigoplus_i (t^{n_i}) \rightarrow \bigoplus_i (t^{p_j})$.

* In particular: if $n \geq p$, any map of modules $\varphi : k[t] \rightarrow k[t], 1 \mapsto p(t)$ determines a map of graded modules

$$\begin{aligned} (t^n) &= \sum^n k[t] \rightarrow (t^p) = \sum^p k[t] \\ t^n &\mapsto (p(t)t^{n-p})t^p \end{aligned}$$

E.g, the identity map on $k[t]$ induces $t^n \mapsto t^{n-p} \cdot t^p$ (The "matrix element" of the identity on $k[t]$ is t^{n-p}). Ditto for direct sums.

* Everything so far works similarly for $\mathbb{Z}[t]$ or $A[t]$, A - common ring. In particular, look again at the simplicial complex



The chain complex is $0 \rightarrow \mathbb{Z}^2 \xrightarrow{\partial_2} \mathbb{Z}^5 \xrightarrow{\partial_1} \mathbb{Z}^4 \rightarrow 0$. The matrices M_2 and M_1 of ∂_2 and ∂_1 without the indicated bases are:

$$M_2 = \begin{matrix} ab \\ bc \\ cd \\ ad \\ ac \end{matrix} \begin{pmatrix} abc & acd \\ 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & -1 \\ -1 & 1 \end{pmatrix}, M_1 = \begin{matrix} d \\ c \\ b \\ a \end{matrix} \begin{pmatrix} ab & bc & cd & ad & ac \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 0 & 1 \\ 1 & -1 & 0 & 0 & 0 \\ -1 & 0 & 0 & -1 & -1 \end{pmatrix}$$

Then ∂_1 (ie M_1) induces a map of $\mathbb{Z}[t]$ - modules $\mathbb{Z}[t]^{\oplus 5} \xrightarrow{M_1} \mathbb{Z}[t]^{\oplus 4}$:

$$\underline{V} = \begin{pmatrix} p_1(t) \\ p_2(t) \\ p_3(t) \\ p_4(t) \\ p_5(t) \end{pmatrix} \mapsto M_1 \underline{V}_\bullet$$

Using the grading (filtration) on the simplicial cx we get a chain complex of graded $\mathbb{Z}[t]$ - modules

$$0 \rightarrow (t^4) \oplus (t^5) \xrightarrow{\partial_2^1} (t)^{\oplus 2} \oplus (t^2)^{\oplus 2} \oplus (t^3) \xrightarrow{\partial_1^1} (t)^{\oplus 2} \oplus (1)^{\oplus 2} \rightarrow 0$$

by the procedure on pg. The respective matrices are (without same bases)

$$M'_2 = \begin{matrix} ab \\ bc \\ cd \\ ad \\ ac \end{matrix} \begin{pmatrix} abc & acd \\ t^3 & 0 \\ t^3 & 0 \\ 0 & t^3 \\ 0 & -t^3 \\ -t^3 & t^3 \end{pmatrix}, M'_1 = \begin{matrix} d \\ c \\ b \\ a \end{matrix} \begin{pmatrix} ab & bc & cd & ad & ac \\ 0 & 0 & t & t & 0 \\ 0 & 1 & -t & 0 & t^2 \\ t & -t & 0 & 0 & 0 \\ -t & 0 & 0 & -t^2 & -t^2 \end{pmatrix}$$

Note: In Carlsson-Zomorodian there is no difference in notation between M_i and M'_i . Also, for the algorithm they order the elements such that the degree decreases down to rows. If we work in $\mathbb{R}[t]$, the matrices will be the same. In $\mathbb{Z}/2\mathbb{Z}[t]$ there won't be difference between ± 1 .

The example from p.1

$$\begin{array}{ccc} a & & b \\ \bullet & & \bullet \\ \deg 0 & & \deg 1 \end{array} \quad \xrightarrow{\quad ab \quad} \bullet$$

The final cx is $0 \rightarrow \mathbb{Z} \xrightarrow{\partial_1} \mathbb{Z}^{\oplus 2} \rightarrow 0$. The matrix of ∂_1 is

$$M_1 = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

. This gives rise to the complexes of $\mathbb{Z}[t]$ - *modules*.

$$0 \rightarrow \mathbb{Z}[t] \xrightarrow{\begin{bmatrix} -1 \\ 1 \end{bmatrix}} \mathbb{Z}t^{\oplus 2} \rightarrow 0$$

and of graded $\mathbb{Z}[t]$ -modules.

$$0 \rightarrow \mathbb{Z}[t] \xrightarrow{\begin{bmatrix} -t \\ t \end{bmatrix}} (1)^{\oplus 2} \rightarrow 0$$

\parallel
 $\mathbb{Z}t^{\oplus 2}$

4.1 Computing Vietoris-Rips persistence barcodes using Ripser

In order to explicitly calculate persistence homology groups of point cloud data, I have created a Python scrip, that randomly generates points in a topological space, with and without noise, and then by using Ripser.py package, it calculates and plots Vietoris-Rips persistence barcodes. The library used is actually a wrapper around the original software written in C++. Before introducing details and results of my implementation, we will consider details in optimization, methodology, computation and implementation of the Ripser software.

Ripser is a software design and implemented to calculate Vietoris-Rips persistence barcodes. The algorithm uses an implicit representation of the co-boundary operator and of the filtration order. Ripser has been optimized by avoiding any explicit construction and storage of the filtration co-boundary matrix, resulting in a significant improvement in time and memory usage.

The predominant approach to persistence computation consist of two steps: the generation of a filtration boundary matrix, and the computation of persistence barcodes using matrix reduction. Often, the construction of the filtration boundary matrix becomes the bottleneck for the computation of Vietoris-Rips barcodes.

That is why, Ripser takes a different approach by avoiding construction and storage of the whole filtration boundary matrix. The algorithm discards parts of the matrix and recomputes them when necessary. To reduce the memory usage, Ripser does not use an explicit matrix data structure, but uses a arithmetic operator, that recomputes the co-boundary map of a simplex whenever needed. The filtration is specified using another algorithmic operator for comparing simplices with respect to their appearance in the filtration order.

The computation of persistent homology implemented in Ripser is based on matrix reduction and uses four key optimizations in order to achieve an efficient implementation:

1. Clearing birth columns: Avoid computation of unnecessary cycles, by using the spectral structure of a boundary matrix D , $D^2 = 0$
2. Cohomology : Using Cohomology to compute persistence barcodes, since it is faster
3. Implicit representation of boundary and reduced boundary matrices: Decouple the description of the filtration and of the boundary operator, representing the boundary matrix only algorithmically instead of explicitly, and to avoid the storage of the entire unreduced and reduced boundary matrices, retaining only the much smaller reduction matrix encoding the column operations
4. Apparent and emergent pairs : The construction of the co-boundary matrix columns can be shortcut when a certain easily identified type of persistence pair, called an emergent co-face pair, is encountered

To construct the algorithm, Ripser Software makes use of simplicial complexes and filtration introduced in chapter 1, with focus on the Vietoris Ripser complex, introduced in section [kejsi ref]. Despite the Vietoris-Rips filtration, a re-indexing and refinement of the filtration is used. In order to compute persistent homology, one needs to apply one further step of re-indexing, refining the essential filtration to an essential simplexwise one.

To ease the computation of the Vietoris-Rips filtration, Ripser makes use of sub-level sets of functions and persistent homology. The Ripser package considers only simplicial homology with coefficients in prime field \mathbb{F}_p . The homology computation is made possible by using simplexwise refinement. A simplexwise filtration gives rise to a filtration boundary matrix, which is the matrix of the boundary operator of the chain complex $C_*(K)$ with respect to the ordered basis given by the oriented simplices in filtration order.

During computation simplices are indexed in a combinatorial number system. Also, Ripser defines a refinement of the Vietoris-Rips filtration to an essential simplexwise filtration, as required for the computation of persistent homology. The simplexes are ordered by increasing diameter, then by increasing dimension and then by decreasing lexicographic vertex order. The result is called the *lexicographically refined Vietoris-Rips filtration*.

4.1.1 Computation and Implementation

In the center of the algorithm for computing persistent homology, there is the matrix reduction method. The matrix reduction method is similar to the one introduced in the previous section. However, since the matrix reduction process can be expensive in time and memory usage, a technique for clearing columns is used. Another interesting approach is the choice to opt for computing persistence barcodes using co-homology instead of homology of Vietoris-Rips filtration. This approach is backed up by de Silva at all [dSMVJ11], and it further optimizes the clearing of columns. Furthermore, as already mentioned before, the matrix reduction is done implicitly. Apart from the computation techniques mentioned above, there are several more optimizations that are presented in detail in [Bau19]

In regards to the implementation, some important data structures of the C++ implementation of Ripser algorithm are:

- Input: The input for Ripser is a finite metric space (X, d) , encoded in a comma (or whitespace, or other nonnumerical character) separated list as either a distance matrix (full, lower, or upper triangular part), or as a list of points in some Euclidean space
- Vertices and Simplices: Vertices are identified with natural numbers $0, \dots, n-1$, where n is the cardinality of the input space. Simplices are indexed by natural numbers according to the combinatorial number system.

- Coefficients: Ripser supports the computation of persistent homology with coefficients in a prime field \mathbb{F}_p , for any prime number $p < 2^{16}$
- Column and matrix data structures: The basic data type for entries in a (*diameter_{entry_t}*) boundary or coefficient matrix is a tuple consisting of a simplex index (*index_t*), a floating point value (*value_t*) caching the diameter of the simplex with that index, and a coefficient (*coef_{f_t}*) if coefficients are enabled.

4.1.2 Details and Results

The Python project is designed and implemented as a command line tool, that would allow the user to enter the name of a common space, the number of points, and the presence or absence of noise.

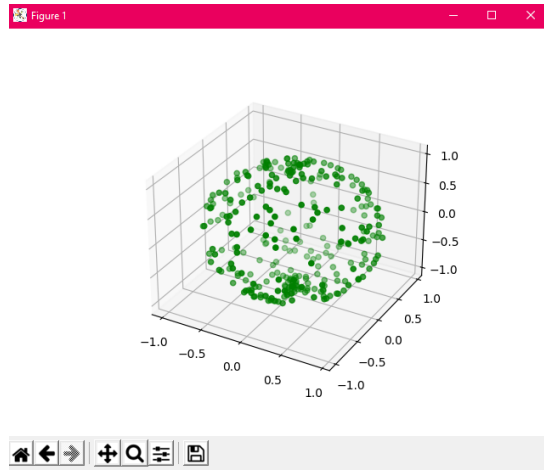
The application can be supplied with 3 different options - “space”, “points”, and “no_noise”. The options “space” (-space or -s) stands for the different types of spaces that can be used. By default a sphere in \mathbb{R}^3 shall be applied. Other options include a cylinder in \mathbb{R}^3 (cylinder_3), a torus in \mathbb{R}^3 (torus_3) and \mathbb{R}^4 (torus_4), klein bottle in \mathbb{R}^4 (klein_bottle_4), projective plane in \mathbb{R}^4 (pro_plane_4) and \mathbb{R}^6 (pro_plane_6). After that, we have a “points” (-points or -p) parameter, indicating the number of points to be generated, where by default 500 shall be outputted. Last, the “no_noise” (-n or -no-noise) parameter is whether or not to add noise to the generated points - it being enabled by default.

The application uniformly generates the number of points inputted by the user into a square 1×1 . Then the resulting points are saved in a n -dimensional array and used as a domain for the functions that are parameterizing surfaces that are included in the application. The points in the square are mapped on the surface of a common space. When the parameter “-n” is passed through the command line to the application, noise is introduced in the mapping of the points to the appropriate surface. The noise can generated randomly as uniform distribution or a Gaussian distribution, where the user can choose the σ and standard deviation, or the bounds for the uniform segment.

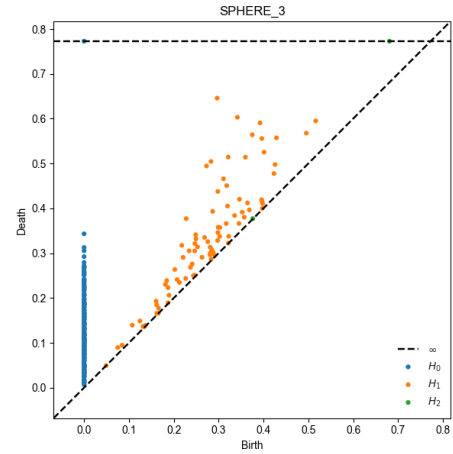
If the space is embedded in \mathbb{R}^3 the points generated on the surface will be plotted in a 3D graph. Regardless the generated points will be outputted on the console. Then the application will pop out a figure of the calculation of Vietoris-Rips persistence barcodes up to the homology specified in the code. Each persistent diagram is a pair (birth time, death time). After that another figure will pop up showing separately the computations of the Vietoris-Rips persistence barcodes in the respective homology. The last graph plots life time of each point instead of birth and death.

Sphere in \mathbb{R}^3 .

Command: `python generator.py -space sphere_3 -points 500`



(a) Plot.



(b) Death birth all together.

Figure 4.1: Plot and Death birth graphs.

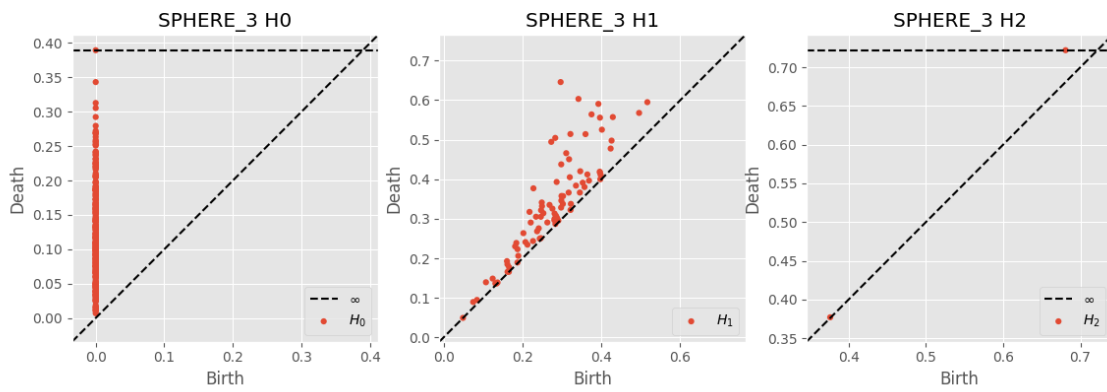


Figure 4.2: Separate homology.

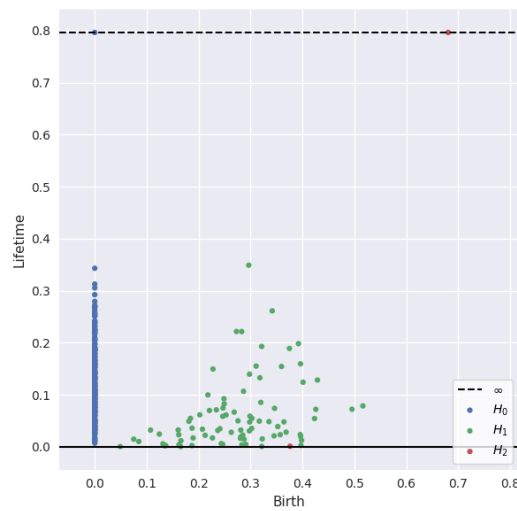
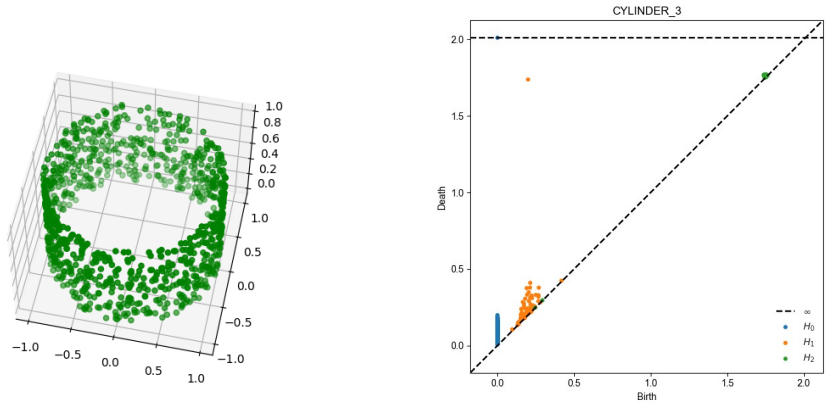


Figure 4.3: Lifetime persistent diagram.

Cylinder in \mathbb{R}^3 .

Command: `python generator.py -space cylinder_3 -points 500`



(a) Plot.

(b) Death birth all together.

Figure 4.4: Plot and Death birth graphs.

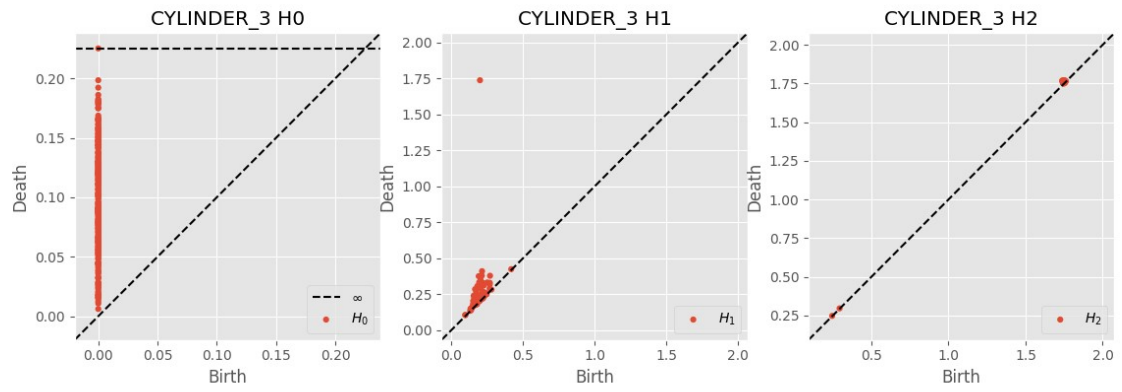


Figure 4.5: Separate homology.

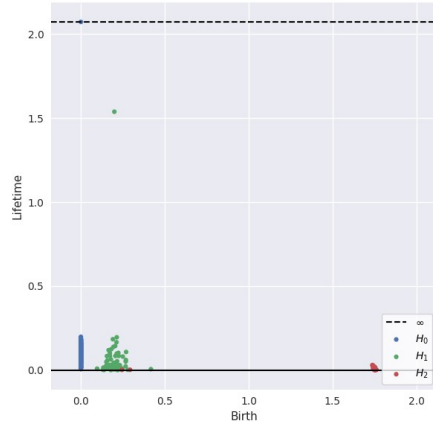
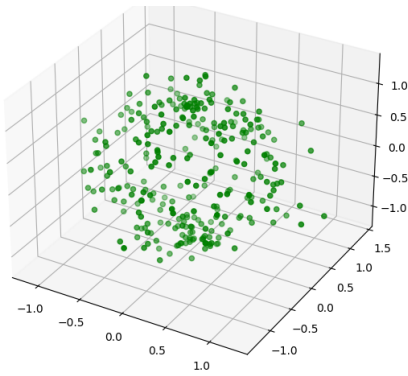


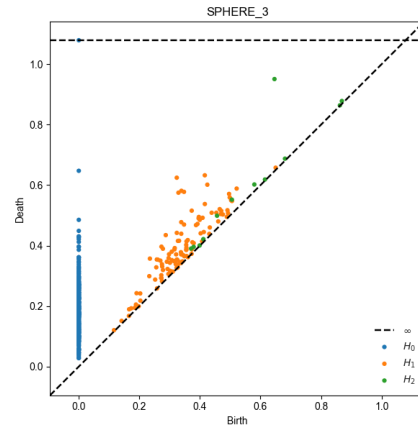
Figure 4.6: Lifetime persistent diagram.

Random Sphere in \mathbb{R}^3 .

Command: `python generator.py -space sphere_3 -points 500 -n`



(a) Plot.



(b) Death birth all together.

Figure 4.7: Plot and Death birth graphs.

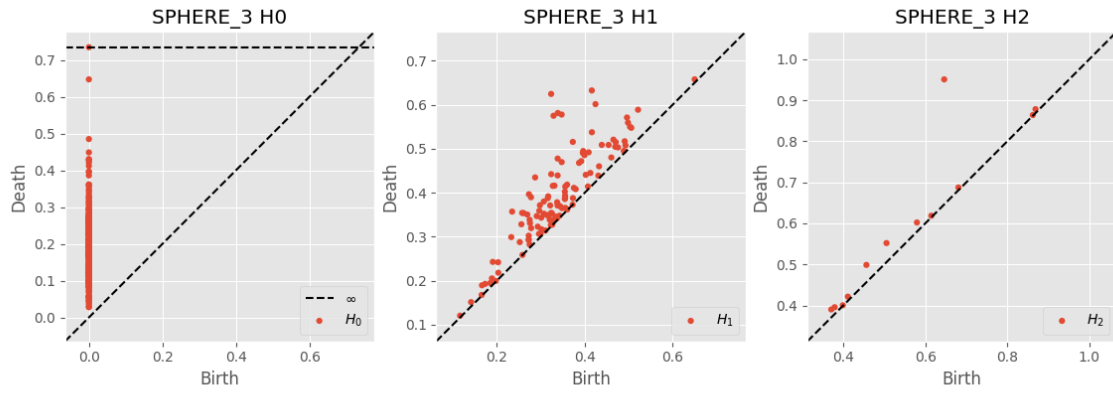


Figure 4.8: Separate homology.

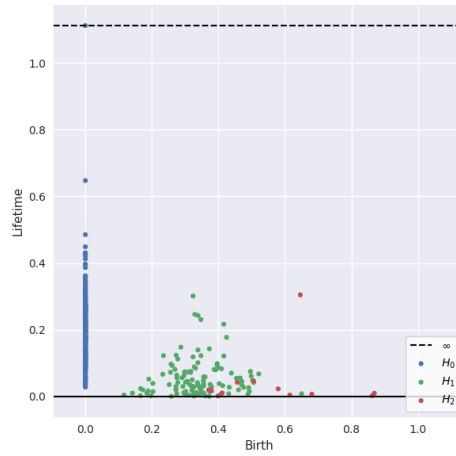
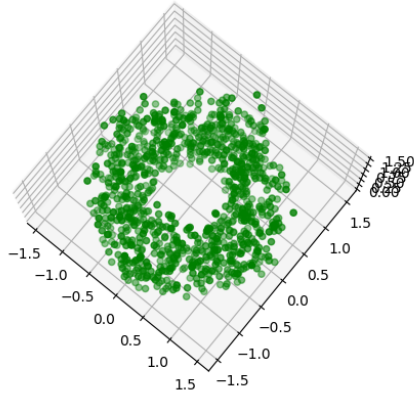


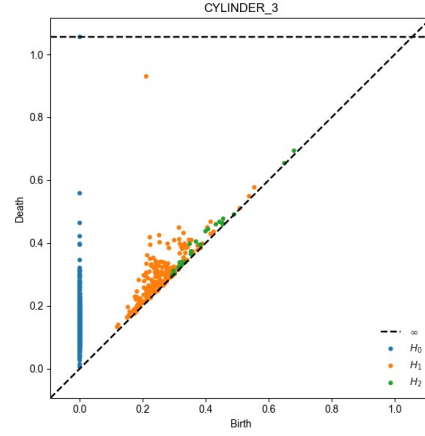
Figure 4.9: Lifetime persistent diagram.

Random Cylinder in \mathbb{R}^3 .

Command: `python generator.py -space cylinder_3 -points 500 -n`



(a) Plot.



(b) Death birth all together.

Figure 4.10: Plot and Death birth graphs.

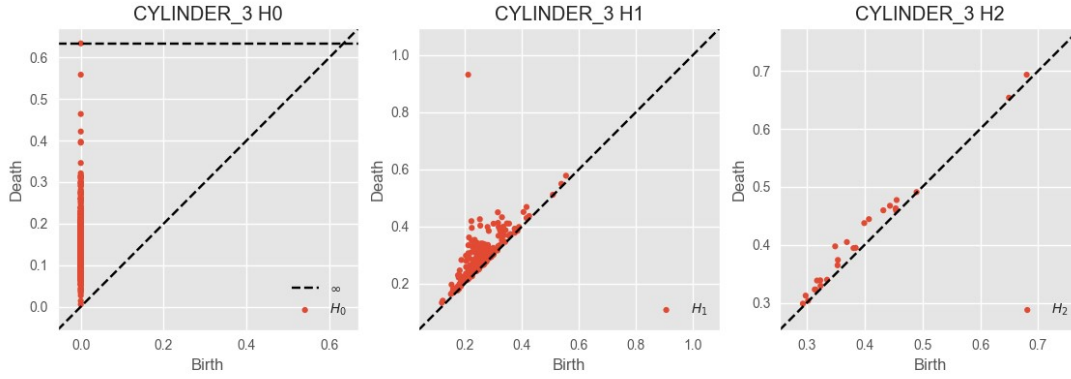


Figure 4.11: Separate homology.

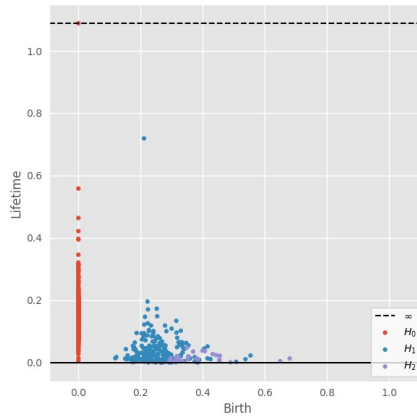


Figure 4.12: Lifetime persistent diagram.

Bibliography

- [Bau19] Ulrich Bauer. Ripser: efficient computation of vietoris-rips persistence barcodes. *arXiv:1908.02518 [cs, math]*, Aug 2019. arXiv: 1908.02518.
- [dSMVJ11] Vin de Silva, Dmitriy Morozov, and Mikael Vejdemo-Johansson. Dualities in persistent (co)homology. *Inverse Problems*, 27(12):124003, Dec 2011.
- [Hat02] Allen Hatcher. *Algebraic topology*. Cambridge University Press, Cambridge, 2002.
- [ZC05] Afra Zomorodian and Gunnar Carlsson. Computing persistent homology. *Discrete and Computational Geometry*, 33(2):249–274, Feb 2005.