



Inspiring Excellence

Algebraic Topology III (MAT484)

Lecture Notes

Preface

This series of lecture notes has been prepared for aiding students who took the BRAC University course **Algebraic Topology III (MAT484)** in Spring 2023 semester. These notes were typeset under the supervision of mathematician **Dr. Syed Hasibul Hassan Chowdhury**. The main goal of this typeset is to have an organized digital version of the notes, which is easier to share and handle. Lecture notes of the previous Algebraic Topology courses can be found in the following links.

- **Algebraic Topology I (MAT431)**: https://atonurc.github.io/assets/MAT431_AT1.pdf
- **Algebraic Topology II (MAT432)**: https://atonurc.github.io/assets/MAT432_AT2.pdf

If you see any mistakes or typos, please send me an email at atonuroychowdhury@gmail.com

Atonu Roy Chowdhury

References:

- *Elements of Algebraic Topology*, by James R. Munkres
- *Foundations of Algebraic Topology*, by Samuel Eilenberg & Norman E. Steenrod
- *Axiomatic Approach to Homology Theory*, by Samuel Eilenberg & Norman E. Steenrod. Link to the paper: <https://www.pnas.org/content/pnas/31/4/117.full.pdf>

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1 Singular Homology Theory

§1.1 Singular Homology Groups

Let \mathbb{R}^∞ denote the generalized Euclidean space \mathbb{E}^J , with J being the set of positive integers. An element of the vector space \mathbb{R}^∞ is an infinite sequence of real numbers (functions from \mathbb{N} to \mathbb{R}) with finitely many nonzero entries. Let Δ_p denote the p -simplex in \mathbb{R}^∞ having vertices

$$\begin{aligned}\varepsilon_0 &= (1, 0, 0, \dots, 0, \dots), \\ \varepsilon_1 &= (0, 1, 0, \dots, 0, \dots), \\ &\dots \\ \varepsilon_p &= (0, 0, 0, \dots, \underbrace{1}_{(p+1)\text{-th entry}}, \dots).\end{aligned}$$

We call Δ_p the **standard p -simplex**. In this notation, Δ_{p-1} is a face of Δ_p .

Definition 1.1 (Singular p -simplex). Let X be a topological space. We define a **singular p -simplex** of X to be a continuous map $T : \Delta_p \rightarrow X$. The free abelian group generated by singular p -simplices of X is denoted by $S_p(X)$, and is called the **singular chain group** of X in dimension p . We shall denote an element of $S_p(X)$ by a \mathbb{Z} -linear combination of singular p -simplices of X .

Singular means that T could be a “bad” map, i.e. it may not be an imbedding. All we want that T is just continuous. Now, recall that

$$\Delta_p = \left\{ (x_0, x_1, \dots, x_p, 0, \dots) \in \mathbb{R}^\infty \mid 0 \leq x_i \leq 1 \text{ and } \sum_{i=0}^p x_i = 1 \right\}. \quad (1.1)$$

Given $a_0, a_1, \dots, a_p \in \mathbb{R}^\infty$, there is a unique affine map $l_{(a_0, \dots, a_p)} : \Delta_p \rightarrow \mathbb{R}^\infty$ that maps ε_i to a_i . It is defined by

$$\begin{aligned}l_{(a_0, \dots, a_p)}(x_0, x_1, \dots, x_p, 0, \dots) &= \sum_{i=0}^p x_i a_i = \sum_{i=0}^p x_i a_i + a_0 - \sum_{i=0}^p x_i a_0 \\ &= a_0 + \sum_{i=0}^p x_i (a_i - a_0).\end{aligned} \quad (1.2)$$

We call this map the **linear singular simplex** determined by $a_0, a_1, \dots, a_p \in \mathbb{R}^\infty$. Now, what is $l_{(\varepsilon_0, \dots, \varepsilon_p)}$? Observe that

$$l_{(\varepsilon_0, \dots, \varepsilon_p)} \varepsilon_i = l_{(\varepsilon_0, \dots, \varepsilon_p)}(0, \dots, 0, \underbrace{1}_{(i+1)\text{-th entry}}, 0, \dots) = \varepsilon_i. \quad (1.3)$$

Therefore, $l_{(\varepsilon_0, \dots, \varepsilon_p)}$ maps ε_i to itself, for every $i = 0, 1, \dots, p$. Also,

$$l_{(\varepsilon_0, \dots, \varepsilon_p)}(x_0, x_1, \dots, x_p, 0, \dots) = \sum_{i=0}^p x_i \varepsilon_i = (x_0, x_1, \dots, x_p, 0, \dots). \quad (1.4)$$

Therefore, $l_{(\varepsilon_0, \dots, \varepsilon_p)}$ is just the inclusion map of Δ_p into \mathbb{R}^∞ . Now, suppose $(x_0, x_1, \dots, x_{p-1}, 0, \dots) \in \Delta_{p-1}$, so that $\sum_{i=0}^{p-1} x_i = 1$. Then

$$\begin{aligned}l_{(\varepsilon_0, \dots, \widehat{\varepsilon_i}, \dots, \varepsilon_p)}(x_0, x_1, \dots, x_{p-1}, 0, \dots) &= x_0 \varepsilon_0 + \dots + x_{i-1} \varepsilon_{i-1} + 0 \cdot \varepsilon_i + x_{i+1} \varepsilon_{i+1} + \dots + x_{p-1} \varepsilon_p \\ &= (x_0, \dots, x_{i-1}, 0, x_{i+1}, \dots, x_{p-1}, 0, \dots),\end{aligned} \quad (1.5)$$

which is a point on the face of Δ_p opposite to the vertex ε_i . In fact, $l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}$ is a linear homomorphism of Δ_{p-1} into the face of Δ_p that is opposite to the vertex ε_i . In other words,

$$l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)} : \Delta_{p-1} \rightarrow \Delta_p$$

maps Δ_{p-1} to the face of Δ_p opposite to the vertex ε_i . Therefore, given a singular p -simplex $T : \Delta_p \rightarrow X$, one can form the composite

$$T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)} : \Delta_{p-1} \rightarrow X,$$

which is a singular $(p-1)$ -simplex. We think of it as the i -th face of the singular p -simplex T .

Definition 1.2 (Boundary homomorphism). We define $\partial : S_p(X) \rightarrow S_{p-1}(X)$ as follows. If $T : \Delta_p \rightarrow X$ is a singular p -simplex, we define ∂T to be

$$\partial T = \sum_{i=0}^p (-1)^i T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}. \quad (1.6)$$

In other words, ∂T is a formal sum of singular simplices of dimension $p-1$, which are the faces of T .

Remark 1.1 (IMPORTANT!). Note that only the singular p -simplices are maps, not the singular p -chains. The p -chains are just formal sum of continuous maps from Δ_p to X . If T_1 and T_2 are two singular p -simplices, i.e. continuous maps $\Delta_p \rightarrow X$, then $T_1 + T_2$ is **NOT** a map. The sum present here is nothing but a formal notation. So one cannot act $T_1 + T_2$ on a point of Δ_p . For the same reason, ∂T_1 is not a map. It is merely a formal linear combination of the continuous maps $T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}$.

If $f : X \rightarrow Y$ is a continuous map, we define a group homomorphism $f_\# : S_p(X) \rightarrow S_p(Y)$ by defining it on singular p -simplices by the equation

$$f_\#(T) = f \circ T \quad (1.7)$$

for a singular p -simplex T .

$$\begin{array}{ccccc} \Delta_p & \xrightarrow{T} & X & \xrightarrow{f} & Y \\ & \searrow & & \nearrow & \\ & & f \circ T & & \end{array}$$

Theorem 1.1

The homomorphism $f_\#$ commutes with ∂ . Furthermore, $\partial^2 = 0$.

Proof. Given a singular p -simplex T ,

$$\partial f_\#(T) = \partial(f \circ T) = \sum_{i=0}^p (-1)^i (f \circ T) \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}. \quad (1.8)$$

$$f_\#(\partial T) = f_\# \left(\sum_{i=0}^p (-1)^i T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)} \right) = \sum_{i=0}^p (-1)^i f \circ T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}. \quad (1.9)$$

Therefore, $\partial f_\#(T) = f_\#(\partial T)$. Now, to prove $\partial^2 = 0$, we first compute ∂ for linear singular simplices $l_{(a_0, \dots, a_p)}$.

$$\partial l_{(a_0, \dots, a_p)} = \sum_{i=0}^p (-1)^i l_{(a_0, \dots, a_p)} \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}. \quad (1.10)$$

Observe that

$$\begin{aligned} l_{(a_0, \dots, a_p)} \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon_i}, \dots, \varepsilon_p)}(x_0, \dots, x_{p-1}, 0, \dots) &= l_{(a_0, \dots, a_p)}(x_0, \dots, x_{i-1}, 0, x_i x_{p-1}, 0, \dots) \\ &= x_0 a_0 + \dots + x_{i-1} a_{i-1} + 0 \cdot a_i + x_i a_{i+1} + \dots + x_{p-1} a_p \\ &= l_{(a_0, \dots, \widehat{a_i}, \dots, a_p)}(x_0, \dots, x_{p-1}, 0, \dots). \end{aligned} \quad (1.11)$$

Hence,

$$l_{(a_0, \dots, a_p)} \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon_i}, \dots, \varepsilon_p)} = l_{(a_0, \dots, \widehat{a_i}, \dots, a_p)}. \quad (1.12)$$

Therefore, from 1.10, it follows that

$$\partial l_{(a_0, \dots, a_p)} = \sum_{i=0}^p (-1)^i l_{(a_0, \dots, \widehat{a_i}, \dots, a_p)}. \quad (1.13)$$

Let's now evaluate $\partial \partial l_{(a_0, \dots, a_p)}$.

$$\begin{aligned} \partial \partial l_{(a_0, \dots, a_p)} &= \sum_{i=0}^p (-1)^i \partial l_{(a_0, \dots, \widehat{a_i}, \dots, a_p)} \\ &= \sum_{i=0}^p (-1)^i \sum_{j < i} (-1)^j l_{(a_0, \dots, \widehat{a_j}, \dots, \widehat{a_i}, \dots, a_p)} + \sum_{i=0}^p (-1)^i \sum_{j > i} (-1)^{j-1} l_{(a_0, \dots, \widehat{a_i}, \dots, \widehat{a_j}, \dots, a_p)} \\ &= \sum_{i=0}^p \sum_{j < i} (-1)^{i+j} l_{(a_0, \dots, \widehat{a_j}, \dots, \widehat{a_i}, \dots, a_p)} - \sum_{i=0}^p \sum_{j > i} (-1)^{i+j} l_{(a_0, \dots, \widehat{a_i}, \dots, \widehat{a_j}, \dots, a_p)}. \end{aligned} \quad (1.14)$$

Now fix $0 \leq j_0 < i_0 \leq p$. In the first summand of 1.14, the contribution of $i = i_0, j = j_0$ is

$$(-1)^{i_0+j_0} l_{(a_0, \dots, \widehat{a_{j_0}}, \dots, \widehat{a_{i_0}}, \dots, a_p)}. \quad (1.15)$$

On the other hand, in the second summand of 1.14, the contribution of $i = j_0, j = i_0$ is also

$$(-1)^{i_0+j_0} l_{(a_0, \dots, \widehat{a_{j_0}}, \dots, \widehat{a_{i_0}}, \dots, a_p)}. \quad (1.16)$$

These two contributions cancel each other. This way, one finds that the RHS of 1.14 vanishes. Hence,

$$\partial \partial l_{(a_0, \dots, a_p)} = 0. \quad (1.17)$$

In particular,

$$\partial \partial l_{(\varepsilon_0, \dots, \varepsilon_p)} = 0. \quad (1.18)$$

Now, $l_{(\varepsilon_0, \dots, \varepsilon_p)} : \Delta_p \rightarrow \Delta_p$ is continuous, so $l_{(\varepsilon_0, \dots, \varepsilon_p)} \in S_p(\Delta_p)$. Furthermore, it is the identity map as we have seen in 1.4. Since $T : \Delta_p \rightarrow X$ is continuous, we can form $T_{\#} : S_p(\Delta_p) \rightarrow S_p(X)$.

$$T_{\#}(l_{(\varepsilon_0, \dots, \varepsilon_p)}) = T \circ l_{(\varepsilon_0, \dots, \varepsilon_p)} = T \circ \text{id}_{\Delta_p} = T. \quad (1.19)$$

Therefore, using the fact that $T_{\#}$ commutes with ∂ , we obtain

$$\partial \partial T = \partial \partial T_{\#}(l_{(\varepsilon_0, \dots, \varepsilon_p)}) = T_{\#}(\partial \partial l_{(\varepsilon_0, \dots, \varepsilon_p)}) = 0. \quad (1.20)$$

Hence, $\partial^2 T = 0$. ■

Definition 1.3 (Singular homology groups). The family of groups $S_p(X)$ and homomorphisms $\partial_p : S_p(X) \rightarrow S_{p-1}(X)$ is called **singular chain complex** of X , and is denoted by $\mathcal{S}(X)$.

$$\cdots \longrightarrow S_{p+1}(X) \xrightarrow{\partial_{p+1}} S_p(X) \xrightarrow{\partial_p} S_{p-1}(X) \longrightarrow \cdots$$

The homology groups of this chain complex are called the **singular homology groups** of X , and are denoted by $H_p(X)$.

Definition 1.4 (Augmentation map). The chain complex $\mathcal{S}(X)$ is augmented by the homomorphism $\epsilon : S_0(X) \rightarrow \mathbb{Z}$ defined by setting $\epsilon(T) = 1$ for each singular 0-simplex $T : \Delta_0 \rightarrow X$. (A generic singular 0-chain is a \mathbb{Z} -linear combination of singular 0-simplices.)

It's immediate that if T is a singular 1-simplex, then $\epsilon(\partial T) = 0$. Indeed,

$$\epsilon(\partial T) = \epsilon(T \circ l_{(\widehat{\epsilon}_0, \widehat{\epsilon}_1)}) - \epsilon(T \circ l_{(\widehat{\epsilon}_1, \widehat{\epsilon}_0)}) = 0. \quad (1.21)$$

Definition 1.5 (Reduced homology groups). The homology groups of $\{\mathcal{S}(X), \epsilon\}$ are called the **reduced singular homology groups** of X , and are denoted by $\widetilde{H}_p(X)$.

Now, given continuous map $f : X \rightarrow Y$ and $T : \Delta_0 \rightarrow X$ a singular 0-simplex on X , then $f_{\#}(T) = f \circ T : \Delta_0 \rightarrow Y$.

$$\begin{array}{ccccc} \Delta_0 & \xrightarrow{T} & X & \xrightarrow{f} & Y \\ & \searrow & & \nearrow & \\ & & f \circ T & & \end{array}$$

Now, consider the augmented singular chain complexes $\{\mathcal{S}(X), \epsilon^X\}$ and $\{\mathcal{S}(Y), \epsilon^Y\}$. Noting continuous $T : \Delta_0 \rightarrow X$ and $f_{\#}(T) : \Delta_0 \rightarrow Y$, one obtains $\epsilon^X(T) = 1$ and $\epsilon^Y(f_{\#}(T)) = 1$. In other words, the following diagram commutes

$$\begin{array}{ccc} S_0(X) & \xrightarrow{\epsilon^X} & \mathbb{Z} \\ (f_{\#})_0 \downarrow & & \downarrow \text{id} \\ S_0(Y) & \xrightarrow{\epsilon^Y} & \mathbb{Z} \end{array}$$

Therefore, $f_{\#} : S_p(X) \rightarrow S_p(Y)$ is an **augmentation preserving chain map** between $\{\mathcal{S}(X), \epsilon^X\}$ and $\{\mathcal{S}(Y), \epsilon^Y\}$. Thus, $f_{\#}$ induces a homomorphism f_* in both ordinary and reduced singular homology.

In [Theorem 1.1](#), we saw that the chain map $f_{\#}$ commutes with the boundary operator ∂ . In other words, $(f_{\#})_p : S_p(X) \rightarrow S_p(Y)$ takes cycles to cycles and boundaries to boundaries. Suppose $c_p \in Z_p(X) = \text{Ker } \partial_p^X$, so that $\partial_p^X c_p = 0$. Now,

$$\partial_p^Y \left((f_{\#})_p c_p \right) = (f_{\#})_{p-1} (\partial_p^X c_p) = 0. \quad (1.22)$$

Hence, $(f_{\#})_p c_p \in Z_p(Y)$. On the other hand, let $b_p \in B_p(X) = \text{Im } \partial_{p+1}^X$. Then $b_p = \partial_{p+1}^X d_{p+1}$ for some $d_{p+1} \in S_{p+1}(X)$. Then

$$(f_{\#})_p b_p = (f_{\#})_p (\partial_{p+1}^X d_{p+1}) = \partial_{p+1}^Y \left((f_{\#})_{p+1} d_{p+1} \right). \quad (1.23)$$

In other words, $(f_{\#})_p b_p \in B_p(Y)$. This reflects the fact that $(f_{\#})_p : S_p(X) \rightarrow S_p(Y)$ induces a homomorphism between the singular homology groups $(f_*)_p : H_p(X) \rightarrow H_p(Y)$. $(f_*)_p$ is given by

$$(f_*)_p (c_p + B_p(X)) = (f_{\#})_p c_p + B_p(Y). \quad (1.24)$$

If the reduced homology groups of X vanishes in all dimensions, we say that X is **acyclic** (in singular homology).

Theorem 1.2

If $i : X \rightarrow X$ is the identity, then so is $(i_*)_p : H_p(X) \rightarrow H_p(X)$. If $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ are continuous, then $((g \circ f)_*)_p = (g_*)_p \circ (f_*)_p$.

Proof. It is sufficient to show that the equations hold at the chain level. We know from the definition of $(f_\#)_p : S_p(X) \rightarrow S_p(Y)$ that it maps $T \in S_p(X)$ to $f \circ T \in S_p(Y)$. Since $i : X \rightarrow X$ is the identity map,

$$(i_\#)_p(T) = i \circ T = T. \quad (1.25)$$

So $(i_\#)_p : S_p(X) \rightarrow S_p(X)$ is the identity homomorphism. As a result,

$$(i_*)_p(c_p + B_p(X)) = (i_\#)_p c_p + B_p(X) = c_p + B_p(X). \quad (1.26)$$

Therefore, $(i_*)_p = \text{id}_{H_p(X)}$.

Given continuous $f : X \rightarrow Y$ and $g : Y \rightarrow Z$, $((g \circ f)_\#)_p : S_p(X) \rightarrow S_p(Z)$ is defined by

$$((g \circ f)_\#)_p T = (g \circ f) \circ T = g \circ (f \circ T) = (g_\#)_p((f_\#)_p T). \quad (1.27)$$

Therefore, $((g \circ f)_\#)_p = (g_\#)_p \circ (f_\#)_p$. Now, at the homology level, for $c_p + B_p(X) \in H_p(X) = Z_p(X) / B_p(X)$

$$((g \circ f)_*)_p(c_p + B_p(X)) = ((g \circ f)_\#)_p c_p + B_p(Z) = (g_\#)_p((f_\#)_p c_p) + B_p(Z). \quad (1.28)$$

Also,

$$(g_*)_p \circ (f_*)_p(c_p + B_p(X)) = (g_\#)_p((f_\#)_p c_p + B_p(Y)) = (g_\#)_p((f_\#)_p c_p) + B_p(Z). \quad (1.29)$$

From 1.28 and 1.29, we can deduce that $((g \circ f)_*)_p = (g_*)_p \circ (f_*)_p$. ■

Corollary 1.3

If $h : X \rightarrow Y$ is a homeomorphism, then $(h_*)_p : H_p(X) \rightarrow H_p(Y)$ is an isomorphism.

Proof. Both $h : X \rightarrow Y$ and $h^{-1} : Y \rightarrow X$ are continuous, and $h \circ h^{-1} = \text{id}_Y$. Therefore,

$$(h_*)_p \circ ((h^{-1})_*)_p = ((h \circ h^{-1})_*)_p = ((\text{id}_Y)_*)_p = \text{id}_{H_p(Y)}. \quad (1.30)$$

Similarly, starting with $h^{-1} \circ h = \text{id}_X$, we will get $((h^{-1})_*)_p \circ (h_*)_p = \text{id}_{H_p(X)}$. Therefore, $((h^{-1})_*)_p$ is the inverse of $(h_*)_p$. In other words, $(h_*)_p$ is an invertible homomorphism, i.e. an isomorphism. ■

Theorem 1.4

Let X be a topological space. Then $H_0(X)$ is free abelian. If $\{X_\alpha\}$ is the collection of path components of X , and if T_α is a singular 0-simplex with image in X_α for each α , then the homology classes of the chains T_α form a basis for $H_0(X)$. The group $\tilde{H}_0(X)$ is also free abelian; it vanishes if X is path connected. Otherwise, let α_0 be a fixed index, then the homology classes of the chains $T_\alpha - T_{\alpha_0}$ for $\alpha \neq \alpha_0$ form a basis for $\tilde{H}_0(X)$.

Proof. Let $x_\alpha = T_\alpha(\Delta_0) \in X_\alpha$, with $T_\alpha : \Delta_0 \rightarrow X$ being a singular 0-simplex. Here, Δ_0 consists of the point $\varepsilon_0 = (1, 0, 0, \dots) \in \mathbb{R}^\infty$. Also, let $T : \Delta_0 \rightarrow X$ be any singular 0-simplex such that $T(\Delta_0) \in X_\alpha$. Since X_α is path connected, there is a path connecting $T(\Delta_0)$ and $T_\alpha(\Delta_0)$. In other words, there is a singular 1-simplex $f : \Delta_1 \rightarrow X$ such that

$$f(1, 0, 0, \dots) = T(\Delta_0) \text{ and } f(0, 1, 0, \dots) = T_\alpha(\Delta_0). \quad (1.31)$$

Then we have

$$\partial_1 f = f \circ l_{(\widehat{\varepsilon}_0, \varepsilon_1)} - f \circ l_{(\varepsilon_0, \widehat{\varepsilon}_1)}. \quad (1.32)$$

Now,

$$f \circ l_{(\varepsilon_0, \widehat{\varepsilon}_1)}(1, 0, 0, \dots) = f(1, 0, 0, \dots) = T(\Delta_0) = T(1, 0, 0, \dots), \quad (1.33)$$

$$f \circ l_{(\widehat{\varepsilon}_0, \varepsilon_1)}(1, 0, 0, \dots) = f(0, 1, 0, \dots) = T_\alpha(\Delta_0) = T_\alpha(1, 0, 0, \dots). \quad (1.34)$$

Therefore, $\partial_1 f = T_\alpha - T$.

An arbitrary singular 0-chain is a \mathbb{Z} -linear combination of singular 0-simplices. Let's take $c \in S_0(X)$. Then $c = \sum_\beta m_\beta T'_\beta$, with $m_\beta \in \mathbb{Z}$ and T'_β being singular 0-simplices. Each $T'_\beta(\Delta_0)$ belongs to some X_α , and hence homologous to T_α . Therefore, c is homologous to some \mathbb{Z} -linear combination $\sum_\alpha n_\alpha T_\alpha$ of the T_α 's. We will now show that no such nontrivial 0-chain $\sum_\alpha n_\alpha T_\alpha$ bounds.

Assume the contrary that $\sum_\alpha n_\alpha T_\alpha = \partial_1 d$ for some $d \in S_1(X)$. Now, the singular 1-chain d is a formal linear combination of singular 1-simplices with path connected image, i.e. the image lies in one of the path components X_α . Thus we can write $d = \sum_\alpha d_\alpha$, where d_α consists of the terms whose images are in X_α . Therefore,

$$\sum_\alpha n_\alpha T_\alpha = \partial_1 d = \sum_\alpha \partial_1 d_\alpha. \quad (1.35)$$

Hence, we get

$$n_\alpha T_\alpha = \partial_1 d_\alpha \quad (1.36)$$

for each α . Applying ϵ to both sides of 1.36, we get

$$\epsilon(n_\alpha T_\alpha) = \epsilon(\partial_1 d_\alpha) \implies n_\alpha = 0. \quad (1.37)$$

Therefore, no non-trivial 0-chain $\sum_\alpha n_\alpha T_\alpha$ bounds. Since every 0-chain is automatically a 0-cycle, an element of $H_0(X)$ is homologous to a 0-chain of the form $\sum_\alpha n_\alpha T_\alpha$. Hence, the homology classes of the singular 0-simplices $\{T_\alpha\}$ form a basis for the free abelian group $H_0(X)$.

$$S_1(X) \xrightarrow{\partial_1} S_0(X) \xrightarrow{\epsilon} \mathbb{Z}$$

$\tilde{H}_0(X)$ is defined as $\tilde{H}_0(X) = \text{Ker } \epsilon / \text{Im } \partial_1$. Given a singular 0-chain $T \in S_0(X)$, we've seen that T is homologous to a 0-chain of the form $T' = \sum_\alpha n_\alpha T_\alpha$; and T' bounds iff $T' = 0$, i.e. $n_\alpha = 0$ for every α . If further $T \in \text{Ker } \epsilon$, then $\epsilon(T) = 0$. Since T and T' are homologous, $T = T' + \partial_1 d$ for some $d \in S_1(X)$. Therefore,

$$0 = \epsilon(T) = \epsilon(T') + \epsilon(\partial_1 d) = \epsilon\left(\sum_\alpha n_\alpha T_\alpha\right) = \sum_\alpha n_\alpha. \quad (1.38)$$

If X is path connected, there is only one component, and hence there is only one n_α involved. Thus $n_\alpha = 0$ from 1.38. This gives us $T' = 0$, leading to the fact that every $T \in \text{Ker } \epsilon$ is homologous to 0, i.e. $T = 0 + \partial_1 d$ for some $d \in S_1(X)$. So $\text{Ker } \epsilon = \text{Im } \partial_1$. Therefore, $\tilde{H}_0(X) = 0$, when X is path connected.

Now, suppose X has more than one path components. Fix α_0 . Then from 1.38, we get

$$0 = \sum_\alpha n_\alpha = n_{\alpha_0} + \sum_{\alpha \neq \alpha_0} n_\alpha \implies n_{\alpha_0} = - \sum_{\alpha \neq \alpha_0} n_\alpha. \quad (1.39)$$

Then T' is

$$T' = \sum_{\alpha} n_{\alpha} T_{\alpha} = \sum_{\alpha \neq \alpha_0} n_{\alpha} T_{\alpha} + n_{\alpha_0} T_{\alpha_0} = \sum_{\alpha \neq \alpha_0} n_{\alpha} T_{\alpha} - \sum_{\alpha \neq \alpha_0} n_{\alpha} T_{\alpha_0} = \sum_{\alpha \neq \alpha_0} n_{\alpha} (T_{\alpha} - T_{\alpha_0}). \quad (1.40)$$

1.40 suggests that T' is a linear combination of the singular 0-chains $\{T_{\alpha} - T_{\alpha_0}\}_{\alpha \neq \alpha_0}$. And T' bounds iff it is trivial, as shown earlier. Therefore, the homology classes of 0-chains $\{T_{\alpha} - T_{\alpha_0}\}_{\alpha \neq \alpha_0}$ form a basis for $\tilde{H}_0(X)$. ■

Theorem 1.4 illustrates the following result:

$$H_p(X) = \begin{cases} \tilde{H}_p(X) & \text{if } p > 0 \\ \tilde{H}_0(X) \oplus \mathbb{Z} & \text{if } p = 0 \end{cases}. \quad (1.41)$$

§1.2 Bracket Operation

Definition 1.6 (Star convex set). A set $X \subseteq \mathbb{E}^J$ is said to be **star convex** relative to the point $w \in X$, if for each $x \in X$, the line segment from x to w lies in X .

Definition 1.7 (Bracket operation). Suppose $X \in \mathbb{E}^J$ is star convex relative to w . We define bracket operation on singular chains of X . Let us first define it for singular p -simplices. Let $T : \Delta_p \rightarrow X$ be a singular p -simplex of X . Define a singular $(p+1)$ -simplex

$$[T, w] : \Delta_{p+1} \rightarrow X$$

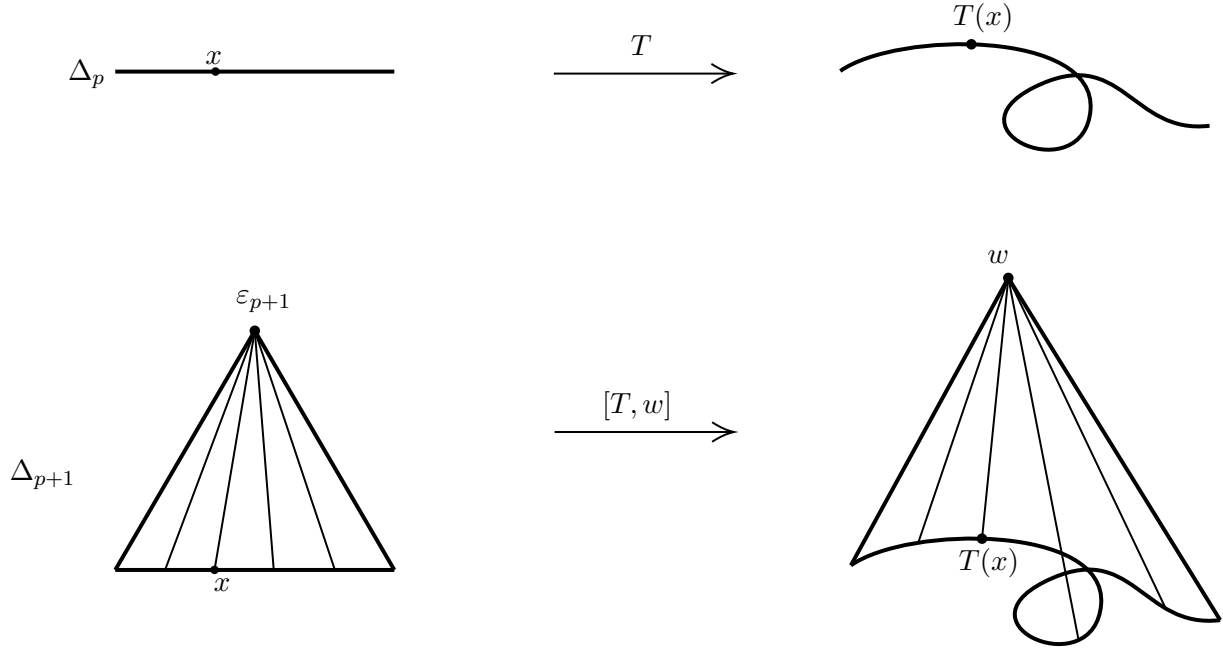
by letting $[T, w]$ carry the line segment from x to ε_{p+1} , for $x \in \Delta_p$ (the collection of all such line segments as x varies in Δ_p constitutes Δ_{p+1}), linearly onto the line segment $T(x)$ to w in X . In other words,

$$[T, w](t\varepsilon_{p+1} + (1-t)x) = tw + (1-t)T(x), \quad (1.42)$$

for $t \in [0, 1]$. Now, extend the definition of bracket operation to arbitrary p -chains as follows: if $c = \sum n_i T_i$ is a singular p -chain of X with each T_i being a singular p -simplex, then we define

$$[c, w] = \sum n_i [T_i, w]. \quad (1.43)$$

In other words, $[\cdot, w] : S_p(X) \rightarrow S_{p+1}(X)$, $c \mapsto [c, w]$ is a homomorphism.



From the diagram above, it's immediate that the restriction of $[T, w]$ to the face Δ_p of Δ_{p+1} is just the map T . Now, consider the case when T is the linear singular simplex $l_{(a_0, \dots, a_p)}$ for $a_0, \dots, a_p \in \mathbb{R}^\infty$. We want to calculate what $[l_{(a_0, \dots, a_p)}, w]$ is.

Recall that $l_{(a_0, \dots, a_p)} : \Delta_p \rightarrow \mathbb{R}^\infty$ is defined as

$$l_{(a_0, \dots, a_p)}(x_0, \dots, x_p) = \sum_{i=0}^p x_i a_i. \quad (1.44)$$

Consider a point $(x_0, \dots, x_p, x_{p+1}, 0, \dots) \in \Delta_{p+1}$. We want to see where $[l_{(a_0, \dots, a_p)}, w]$ takes this point to. Since $(x_0, \dots, x_p, x_{p+1}, 0, \dots) \in \Delta_{p+1}$, each x_i is nonnegative with $\sum_{i=0}^{p+1} x_i = 1$. Now,

$$\sum_{i=0}^p \frac{x_i}{1 - x_{p+1}} = 1, \quad (1.45)$$

so $\left(\frac{x_0}{1 - x_{p+1}}, \frac{x_1}{1 - x_{p+1}}, \dots, \frac{x_p}{1 - x_{p+1}}, 0, \dots\right) \in \Delta_p$. Therefore,

$$(x_0, \dots, x_p, x_{p+1}, 0, \dots) = (1 - x_{p+1}) \left(\frac{x_0}{1 - x_{p+1}}, \frac{x_1}{1 - x_{p+1}}, \dots, \frac{x_p}{1 - x_{p+1}}, 0, \dots\right) + x_{p+1} \varepsilon_{p+1}. \quad (1.46)$$

By the definition of bracket operation,

$$\begin{aligned} & [l_{(a_0, \dots, a_p)}, w](x_0, \dots, x_p, x_{p+1}, 0, \dots) \\ &= (1 - x_{p+1}) l_{(a_0, \dots, a_p)} \left(\frac{x_0}{1 - x_{p+1}}, \frac{x_1}{1 - x_{p+1}}, \dots, \frac{x_p}{1 - x_{p+1}}, 0, \dots\right) + x_{p+1} w \\ &= (1 - x_{p+1}) \sum_{i=0}^p \frac{x_i}{1 - x_{p+1}} a_i + x_{p+1} w \\ &= \sum_{i=0}^p x_i a_i + x_{p+1} w. \end{aligned} \quad (1.47)$$

Furthermore,

$$l_{(a_0, \dots, a_p, w)}(x_0, \dots, x_p, x_{p+1}, 0, \dots) = x_0 a_0 + \dots + x_p a_p + x_{p+1} w = \sum_{i=0}^p x_i a_i + x_{p+1} w. \quad (1.48)$$

Equating 1.47 and 1.48, we get

$$[l_{(a_0, \dots, a_p)}, w] = l_{(a_0, \dots, a_p, w)}. \quad (1.49)$$

Now we will show that $[T, w] : \Delta_{p+1} \rightarrow X$ is continuous. We have seen earlier that given $x \in \Delta_p$, a point in Δ_{p+1} is expressed as $t\varepsilon_{p+1} + (1-t)x$, with $0 \leq t \leq 1$. Hence, we are concerned with the following quotient map $\pi : \Delta_p \times [0, 1] \rightarrow \Delta_{p+1}$ defined by

$$\pi(x, t) = t\varepsilon_{p+1} + (1-t)x. \quad (1.50)$$

If $x = (x_0, \dots, x_p, 0, \dots) \in \Delta_p$, then 1.50 takes the familiar form

$$\pi((x_0, \dots, x_p, 0, \dots), t) = ((1-t)x_0, \dots, (1-t)x_p, t, 0, \dots). \quad (1.51)$$

Observe that $\pi|_{\Delta_p \times [0, 1]} : \Delta_p \times [0, 1] \rightarrow \Delta_{p+1}$ is 1-1, and $\pi(\Delta_p \times \{1\}) = \{\varepsilon_{p+1}\}$, showing that π collapses $\Delta_p \times \{1\}$ to the $(p+1)$ -th vertex ε_{p+1} of Δ_{p+1} . Now, the continuous map $f : \Delta_p \times [0, 1] \rightarrow X$ defined by

$$f(x, t) = tw + (1-t)T(x) \quad (1.52)$$

is constant on $\Delta_p \times \{1\}$. In fact, $f(\Delta_p \times \{1\}) = \{w\}$. Since π is 1-1 for other points, f is seen to be constant for $\pi^{-1}(y)$ with $y \in \Delta_{p+1} \setminus \{\varepsilon_{p+1}\}$. In other words, $f : \Delta_p \times [0, 1] \rightarrow X$ is constant for each $\pi^{-1}(y)$ with $y \in \Delta_{p+1}$. Therefore, f induces a unique continuous map $\tilde{f} : \Delta_{p+1} \rightarrow X$ such that the following diagram commutes

$$\begin{array}{ccc} \Delta_p \times [0, 1] & & \\ \pi \downarrow & \searrow f & \\ \Delta_{p+1} & \xrightarrow{\tilde{f}} & X \end{array}$$

This unique map \tilde{f} is precisely $[T, w]$, since

$$([T, w] \circ \pi)(x, t) = [T, w](t\varepsilon_{p+1} + (1-t)x) = tw + (1-t)T(x) = f(x, t). \quad (1.53)$$

Therefore, $\tilde{f} = [T, w]$, and hence it is continuous. So $[T, w]$ is indeed a singular $(p+1)$ -simplex.

Lemma 1.5

Let X be a star convex set with respect to w ; let c be a singular p -chain of X . Then

$$\partial[c, w] = \begin{cases} [\partial c, w] + (-1)^{p+1} c & \text{if } p > 0 \\ \epsilon(c)T_w - c & \text{if } p = 0 \end{cases}, \quad (1.54)$$

where T_w is the singular 0-simplex mapping Δ_0 to w .

Proof. If T is a singular 0-simplex, $[T, w]$ is a singular 1-simplex. Then

$$\partial[T, w] = [T, w] \circ l_{(\widehat{\varepsilon}_0, \varepsilon_1)} - [T, w] \circ l_{(\varepsilon_0, \widehat{\varepsilon}_1)}. \quad (1.55)$$

Now, recall $[T, w] : \Delta_1 \rightarrow X$ maps the line joining ε_1 to ε_0 to the line joining w to $T(\varepsilon_0)$. So

$$[T, w](1-t, t, 0, \dots) = tw + (1-t)T(\varepsilon_0). \quad (1.56)$$

Now,

$$([T, w] \circ l_{(\widehat{\varepsilon}_0, \varepsilon_1)})(1, 0, \dots) = [T, w](0, 1, 0, \dots) = w = T_w(1, 0, \dots). \quad (1.57)$$

Therefore, $([T, w] \circ l_{(\widehat{\varepsilon}_0, \varepsilon_1)}) = T_w$.

$$([T, w] \circ l_{(\varepsilon_0, \widehat{\varepsilon}_1)})(1, 0, \dots) = [T, w](1, 0, \dots) = T(\varepsilon_0) = T(1, 0, \dots), \quad (1.58)$$

so $[T, w] \circ l_{(\varepsilon_0, \widehat{\varepsilon}_1)} = T$. By 1.55, we get

$$\partial [T, w] = T_w - T. \quad (1.59)$$

Now, let $c = \sum_i n_i T_i$ be a singular 0-chain with T_i being singular 0-simplices. Then

$$\partial \left[\sum_i n_i T_i, w \right] = \sum_i n_i \partial [T_i, w] = \sum_i n_i (T_w - T_i) = \left(\sum_i n_i \right) T_w - \sum_i n_i T_i. \quad (1.60)$$

Now, applying the augmentation map to c , we get

$$\epsilon(c) = \epsilon \left(\sum_i n_i T_i \right) = \sum_i n_i \epsilon(T_i) = \sum_i n_i. \quad (1.61)$$

Therefore, 1.60 gives us

$$\partial [c, w] = \epsilon(c) T_w - c. \quad (1.62)$$

Now we shall consider the case when T is a singular p -simplex, and we shall prove that $\partial [T, w] = [\partial T, w] + (-1)^{p+1} T$.

$$\begin{aligned} \partial [T, w] &= \sum_{i=0}^{p+1} (-1)^i [T, w] \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_{p+1})} \\ &= \sum_{i=0}^p (-1)^i [T, w] \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_{p+1})} + (-1)^{p+1} [T, w] \circ l_{(\varepsilon_0, \dots, \varepsilon_p, \widehat{\varepsilon}_{p+1})}. \end{aligned} \quad (1.63)$$

$l_{(\varepsilon_0, \dots, \varepsilon_p, \widehat{\varepsilon}_{p+1})}$ is the inclusion map of Δ_p into Δ_{p+1} . So $[T, w] \circ l_{(\varepsilon_0, \dots, \varepsilon_p, \widehat{\varepsilon}_{p+1})}$ is nothing but the restriction of $[T, w]$ to Δ_p , which is the same as T . Now we want to show that

$$[T, w] \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_{p+1})} = [T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}, w]. \quad (1.64)$$

Both sides of 1.64 are maps from Δ_p to X . Let $(x_0, \dots, x_p, 0, \dots) \in \Delta_p$. Then

$$([T, w] \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_{p+1})})(x_0, \dots, x_p, 0, \dots) = [T, w](x_0, \dots, x_{i-1}, 0, x_i, \dots, x_{p-1}, x_p, 0, \dots). \quad (1.65)$$

Now, $(x_0, \dots, x_{i-1}, 0, x_i, \dots, x_{p-1}, x_p, 0, \dots)$ is a point in Δ_{p+1} . We can write it as

$$(x_0, \dots, x_{i-1}, 0, x_i, \dots, x_{p-1}, x_p, 0, \dots) = (1 - x_p) \left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{i-1}}{1 - x_p}, 0, \frac{x_i}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right) + x_p \varepsilon_{p+1}. \quad (1.66)$$

Now, $\left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{i-1}}{1 - x_p}, 0, \frac{x_i}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right)$ is a point in Δ_p since its nonzero components are all non-negative and they add to 1. Therefore,

$$\begin{aligned} &[T, w](x_0, \dots, x_{i-1}, 0, x_i, \dots, x_{p-1}, x_p, 0, \dots) \\ &= (1 - x_p) T \left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{i-1}}{1 - x_p}, 0, \frac{x_i}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right) + x_p w. \end{aligned} \quad (1.67)$$

On the other hand, we can write $(x_0, \dots, x_p, 0, \dots)$ as

$$(x_0, \dots, x_p, 0, \dots) = (1 - x_p) \left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right) + x_p \varepsilon_p, \quad (1.68)$$

where $\left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right) \in \Delta_{p-1}$. So

$$\begin{aligned} &[T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}, w](x_0, \dots, x_p, 0, \dots) \\ &= x_p w + (1 - x_p) (T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}) \left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right) \\ &= x_p w + (1 - x_p) T \left(\frac{x_0}{1 - x_p}, \dots, \frac{x_{i-1}}{1 - x_p}, 0, \frac{x_i}{1 - x_p}, \dots, \frac{x_{p-1}}{1 - x_p}, 0, \dots \right). \end{aligned} \quad (1.69)$$

Combining 1.65, 1.67 and 1.69, we get that 1.64 indeed holds, i.e.

$$[T, w] \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_{p+1})} = [T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}, w].$$

Now, from 1.63, we then get

$$\begin{aligned} \partial [T, w] &= \sum_{i=0}^p (-1)^i [T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}, w] + (-1)^{p+1} T \\ &= \left[\sum_{i=0}^p (-1)^i T \circ l_{(\varepsilon_0, \dots, \widehat{\varepsilon}_i, \dots, \varepsilon_p)}, w \right] + (-1)^{p+1} T \\ &= [\partial T, w] + (-1)^{p+1} T. \end{aligned} \quad (1.70)$$

Now, if $c = \sum_i n_i T_i$ is a singular p -chain with T_i being singular 0-simplices, then

$$\partial [c, w] = \sum_i n_i \partial [T_i, w] = \sum_i n_i [\partial T_i, w] + (-1)^{p+1} \sum_i n_i T_i = [\partial c, w] + (-1)^{p+1} c. \quad (1.71)$$

■

Theorem 1.6

Let $X \subseteq \mathbb{E}^J$ be star convex with respect to w . Then X is acyclic in singular homology.

Proof. To show that $\tilde{H}_0(X) = 0$, let $c \in \text{Ker } \epsilon$.

$$S_1(X) \xrightarrow{\partial_1} S_0(X) \xrightarrow{\epsilon} \mathbb{Z}$$

So $\epsilon(c) = 0$. Now, by Lemma 1.5,

$$\partial_1 [c, w] = \epsilon(c) T_w - c = -c. \quad (1.72)$$

Hence, $c \in \text{Im } \partial_1$ leading to $\text{Ker } \epsilon \subseteq \text{Im } \partial_1$. We already know Hence, $\text{Im } \partial_1 \subseteq \text{Ker } \epsilon$. Therefore, $\tilde{H}_0(X) = 0$.

Now we shall show that $H_p(X) = 0$ for $p > 0$. Let $z \in \text{Ker } \partial_p$. Then $\partial_p z = 0$. By Lemma 1.5 again,

$$\partial_{p+1} [z, w] = [\partial_p z, w] + (-1)^{p+1} z = (-1)^{p+1} z. \quad (1.73)$$

Hence, $z \in \text{Im } \partial_{p+1}$. Therefore, $H_p(X) = 0$. In other words, $\tilde{H}_p(X) = 0$ for all p , i.e. X is acyclic. ■

Corollary 1.7

Any simplex is acyclic in singular homology.

§1.3 Relative Homology

If X is a space and A is a subspace of X , there is a natural inclusion $S_p(A) \hookrightarrow S_p(X)$. The group of **relative singular chains** is defined by

$$S_p(X, A) = S_p(X) / S_p(A). \quad (1.74)$$

The boundary operator $\partial_p^X : S_p(X) \rightarrow S_{p-1}(X)$ restricts to the boundary operator on $S_p(A)$, i.e. $\partial_p^X|_{S_p(A)} : S_p(A) \rightarrow S_{p-1}(A)$. It, therefore, induces a boundary operator at the relative singular chain level:

$$\begin{aligned} \partial_p^{(X,A)} : S_p(X, A) &\rightarrow S_{p-1}(X, A), \\ T + S_p(A) &\mapsto \partial_p^X T + S_{p-1}(A), \end{aligned} \quad (1.75)$$

with $T = \sum_{\alpha} n_{\alpha} T_{\alpha}$ being a singular p -chain, where $n_{\alpha} \in \mathbb{Z}$ and T_{α} singular p -simplices. If any of the T_{α} 's are such that $T_{\alpha}(\Delta_p) \subseteq A$, then $T_{\alpha} \in S_p(A)$. So, we can assume $T_{\alpha}(\Delta_p) \setminus A \neq \emptyset$. Such T_{α} 's generate the group $S_p(X, A)$, and so $S_p(X, A)$ is a free abelian group.

The family of groups $S_p(X, A)$ and homomorphisms $\partial_p^{(X,A)}$ is called **the singular chain complex** of the pair (X, A) , and is denoted by $\mathcal{S}(X, A)$. The homology groups of the chain complex $\mathcal{S}(X, A)$ of the pair (X, A) are called the **singular homology groups** of the pair (X, A) , and are denoted by $H_p(X, A)$.

The chain complex $\mathcal{S}(X, A)$ is free, i.e. $S_p(X, A)$ is free for each p . The group $S_p(X, A)$ has as basis all the cosets of the form $T + S_p(A)$, where T is a singular p -simplex with $T(\Delta_p) \setminus A \neq \emptyset$.

If $f : (X, A) \rightarrow (Y, B)$ is a continuous map (recall that by the continuity of f between pairs (X, A) and (Y, B) , we actually mean that $f : X \rightarrow Y$ is continuous, with $f(A) \subseteq B$), then homomorphisms $(f_{\#})_p : S_p(X) \rightarrow S_p(Y)$ carries singular p -chains of A into singular p -chains of B . So it induces a homomorphism (also denoted by $(f_{\#})_p$) at the level of relative singular p -chains:

$$\begin{aligned} (f_{\#})_p : S_p(X, A) &\rightarrow S_p(Y, B), \\ T + S_p(A) &\mapsto (f_{\#})_p T + S_p(B) = f \circ T + S_p(B). \end{aligned} \quad (1.76)$$

where T is a singular p -simplex with $T(\Delta_p) \setminus A \neq \emptyset$. This map can be seen to commute with the boundary operator at the relative singular chain level. To be precise,

$$(f_{\#})_{p-1} \circ \partial_p^{(X,A)} = \partial_p^{(Y,B)} \circ (f_{\#})_p. \quad (1.77)$$

In other words, the following diagram commutes.

$$\begin{array}{ccc} S_p(X, A) & \xrightarrow{\partial_p^{(X,A)}} & S_{p-1}(X, A) \\ (f_{\#})_p \downarrow & & \downarrow (f_{\#})_{p-1} \\ S_p(Y, B) & \xrightarrow{\partial_p^{(Y,B)}} & S_{p-1}(Y, B) \end{array}$$

Therefore, $f_{\#}$ induces a homomorphism

$$\begin{aligned} (f_{*})_p : H_p(X, A) &\rightarrow H_p(Y, B), \\ c + \text{Im } \partial_{p+1}^{(X,A)} &\mapsto (f_{\#})_p c + \text{Im } \partial_{p+1}^{(Y,B)}. \end{aligned} \quad (1.78)$$

Theorem 1.8

If $i : (X, A) \rightarrow (X, A)$ is the identity, then so is $(i_{*})_p : H_p(X, A) \rightarrow H_p(X, A)$. If $h : (X, A) \rightarrow (Y, B)$ and $k : (Y, B) \rightarrow (Z, C)$ are continuous, then $((k \circ h)_{*})_p = (k_{*})_p \circ (h_{*})_p$.

Proof. Since $(i_{\#})_p : S_p(X) \rightarrow S_p(X)$ is the identity map (as proven while proving [Theorem 1.2](#)), so is $(i_{\#})_p : S_p(X, A) \rightarrow S_p(X, A)$. Then from [1.78](#), we get that $(i_{*})_p : H_p(X, A) \rightarrow H_p(X, A)$ is the identity, i.e. $(i_{*})_p = \text{id}_{H_p(X,A)}$.

Now, let us prove $((k \circ h)_{\#})_p = (k_{\#})_p \circ (h_{\#})_p$. The equality at the homology level will then follow from [1.78](#).

$$(h_{\#})_p : S_p(X, A) \rightarrow S_p(Y, B), \quad (k_{\#})_p : S_p(Y, B) \rightarrow S_p(Z, C).$$

We choose a singular p -simplex T such that $T(\Delta_p) \setminus A \neq \emptyset$. Then the cosets of the form $T + S_p(A)$ form a basis of $S_p(X, A)$.

$$\begin{array}{ccccc} \Delta_p & \xrightarrow{T} & X & \xrightarrow{h} & Y & \xrightarrow{k} & Z \\ & & & \searrow & \text{coh} & \nearrow & \\ & & & & & & \end{array}$$

Using 1.76, we get

$$(h_{\#})_p(T + S_p(A)) = h \circ T + S_p(B), \quad (1.79)$$

$$(k_{\#})_p((h_{\#})_p(T + S_p(A))) = (k_{\#})_p(h \circ T + S_p(B)) = k \circ h \circ T + S_p(C), \quad (1.80)$$

$$((k \circ h)_{\#})_p(T + S_p(A)) = k \circ h \circ T + S_p(C). \quad (1.81)$$

Therefore, we can conclude that $((k \circ h)_{\#})_p = (k_{\#})_p \circ (h_{\#})_p$. ■

Theorem 1.9

There is a homomorphism $(\partial_*)_p : H_p(X, A) \rightarrow H_{p-1}(A)$, defined for $A \subset X$ and all p , such that the sequence

$$\cdots \longrightarrow H_p(A) \xrightarrow{(i_*)_p} H_p(X) \xrightarrow{(\pi_*)_p} H_p(X, A) \xrightarrow{(\partial_*)_p} H_{p-1}(A) \longrightarrow \cdots$$

is exact, where i and π are the inclusions

$$(A, \emptyset) \xhookrightarrow{i} (X, \emptyset) \xhookrightarrow{\pi} (X, A).$$

The same holds if reduced homology is used for X and A , provided $A \neq \emptyset$.

A continuous map $f : (X, A) \rightarrow (Y, B)$ induces a homomorphism of the corresponding exact sequences in singular homology, either ordinary or reduced.

Proof. Let us recall the Zig-Zag lemma (Lemma 4.4.1 in the lecture note of AT2). Given a short exact sequence of chain complexes $\mathcal{C} = \{C_p, \partial_p^C\}$, $\mathcal{D} = \{D_p, \partial_p^D\}$ and $\mathcal{E} = \{E_p, \partial_p^E\}$, i.e.

$$0 \longrightarrow \mathcal{C} \xrightarrow{\phi} \mathcal{D} \xrightarrow{\psi} \mathcal{E} \longrightarrow 0$$

with ϕ and ψ being chain maps, i.e. family of homomorphisms $\{\phi_p\}$ and $\{\psi_p\}$ such that

$$0 \longrightarrow C_p \xrightarrow{\phi_p} D_p \xrightarrow{\psi_p} E_p \longrightarrow 0$$

is exact for each p , then there is a long exact homology sequence

$$\begin{array}{ccccccc} & & \cdots & & \cdots & & \\ & & & \nearrow & & & \\ H_p(\mathcal{C}) & \xrightarrow{(\phi_p)_*} & H_p(\mathcal{D}) & \xrightarrow{(\psi_p)_*} & H_p(\mathcal{E}) & & \\ & & \nwarrow & & & & \\ H_{p-1}(\mathcal{C}) & \xrightarrow{(\phi_{p-1})_*} & H_{p-1}(\mathcal{D}) & \longrightarrow & \cdots & & \end{array}$$

$(\partial_*)_p$

We shall use Zig-Zag lemma with $C_p = S_p(A)$, $D_p = S_p(X)$ and $E_p = S_p(X, A)$, with chain maps given as follows:

$$0 \longrightarrow S_p(A) \xrightarrow{(i_*)_p} S_p(X) \xrightarrow{(\pi_*)_p} S_p(X, A) \longrightarrow 0.$$

Then the above sequence is exact, since $S_p(X, A) = S_p(X) / S_p(A)$. Now, Zig-Zag lemma guarantees the existence of the homomorphism $(\partial_*)_p : H_p(X, A) \rightarrow H_{p-1}(A)$ and the following long-exact sequence

$$\cdots \longrightarrow H_p(A) \xrightarrow{(i_*)_p} H_p(X) \xrightarrow{(\pi_*)_p} H_p(X, A) \xrightarrow{(\partial_*)_p} H_{p-1}(A) \longrightarrow \cdots$$

Now, given a continuous map $f : (X, A) \rightarrow (Y, B)$, we shall verify that the following diagram commutes:

$$\begin{array}{ccccccc} 0 & \longrightarrow & S_p(A) & \xrightarrow{(i_{\#})_p} & S_p(X) & \xrightarrow{(\pi_{\#})_p} & S_p(X, A) \longrightarrow 0 \\ & & \left((f|_A)_{\#}\right)_p \downarrow & & \left((f|_X)_{\#}\right)_p \downarrow & & \downarrow (f_{\#})_p \\ 0 & \longrightarrow & S_p(B) & \xrightarrow{(i'_{\#})_p} & S_p(Y) & \xrightarrow{(\pi'_{\#})_p} & S_p(Y, B) \longrightarrow 0 \end{array}$$

Here, by $f|_X$, we mean the map $f : X \rightarrow Y$. First, let's show the commutativity of the left hand square. Let's take a singular p -simplex T of A , i.e. $T : \Delta_p \rightarrow A$ is continuous. Then

$$(i_{\#})_p T = i \circ T = T, \quad (f_{\#})_p \left((i_{\#})_p T \right) = f \circ T. \quad (1.82)$$

$$\left((f|_A)_{\#} \right)_p T = f|_A \circ T = f \circ T, \quad (i'_{\#})_p \left(\left((f|_A)_{\#} \right)_p T \right) = i' \circ f \circ T = f \circ T. \quad (1.83)$$

$f|_A \circ T = f \circ T$ because the image of T lies entirely in A . Therefore, the left hand square commutes. Now we shall show that the right hand square commutes as well. Let's take a singular p -simplex T of X , i.e. $T : \Delta_p \rightarrow X$ is continuous.

$$(\pi_{\#})_p T = T + S_p(A), \quad (f_{\#})_p \left((\pi_{\#})_p T \right) = (f_{\#})_p T + S_p(B) = (\pi'_{\#})_p \left((f_{\#})_p T \right). \quad (1.84)$$

Therefore, the right hand square commutes. So the diagram is commutative. Now, applying Theorem 5.1.1 from the lecture note of [AT2](#), we obtain that the following diagram commutes:

$$\begin{array}{ccccccccccc} \cdots & \longrightarrow & H_p(A) & \xrightarrow{(i_{*})_p} & H_p(X) & \xrightarrow{(\pi_{*})_p} & H_p(X, A) & \xrightarrow{(\partial_{*})_p} & H_{p-1}(A) & \longrightarrow & \cdots \\ & & \left((f|_A)_{*}\right)_p \downarrow & & (f_{*})_p \downarrow & & \downarrow (f_{*})_p & & \downarrow \left((f|_A)_{*}\right)_{p-1} & & \\ \cdots & \longrightarrow & H_p(B) & \xrightarrow{(i'_{*})_p} & H_p(Y) & \xrightarrow{(\pi'_{*})_p} & H_p(Y, B) & \xrightarrow{(\partial'_{*})_p} & H_{p-1}(B) & \longrightarrow & \cdots \end{array}$$

This establishes the induced homomorphisms between the respective long exact sequences of the singular homology. Following the same procedure, one can show that the same result holds in reduced homology. ■