

MATH592
Introduction to Algebraic Topology

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Abstract

This is a graduate-level course taught by [Jennifer Wilson](#) about algebraic topology. It is self-contained enough that only requires a background in abstract algebra and some point set topology. We will use Hatcher [\[HPM02\]](#) as the main text, but the order may differ here and there. Enjoy this fun course! In particular, I add some extra content which is not covered in lectures, things like [groupoid](#), [fibered coproduct](#), feel free to skip these content.

$$\chi \left(\text{a purple circle} \right) = 1 = \chi \left(\text{a complex 3D mesh object} \right)$$

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Chapter 1

Foundation of Algebraic Topology

In this chapter, we'll give a few, but important definitions which will be used throughout the discussion of this course. This will help us build up a solid understanding about spaces we're working on both mathematically and visually.

Lecture 1: Homotopies of Maps

1.1 Homotopy

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We start with the most important and fundamental concept, [homotopy](#).

Definition. Let X, Y be topological spaces, and $f, g: X \rightarrow Y$ being two continuous maps.

Definition 1.1.1 (Homotopy). A *homotopy* from f to g is a 1-parameter family of maps that continuously deforms f to g , i.e., it's a continuous function $F: X \times I \rightarrow Y$, where $I = [0, 1]$, such that

$$F(x, 0) = f(x), \quad F(x, 1) = g(x).$$

We often write $F_t(x)$ for $F(x, t)$.

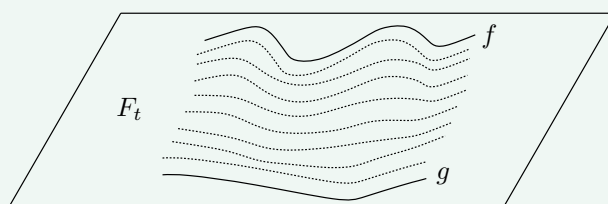


Figure 1.1: The continuous deforming from f to g described by F_t

Definition 1.1.2 (Homotopic). If a [homotopy](#) exists between f and g , we say they are *homotopic* and write

$$f \simeq g.$$

Definition 1.1.3 (Nullhomotopic). If f is [homotopic](#) to a constant map, we call it *nullhomotopic*.

Remark. Later, we'll not state that a map is continuous explicitly since we almost always assume this in this context.

Example (Straight line homotopy). Any two (continuous) maps with specification

$$f, g: X \rightarrow \mathbb{R}^n$$

are **homotopic** by considering

$$F_t(x) = (1-t)f(x) + tg(x).$$

We call it the *straight line homotopy*.

Example. Let S^1 denotes the unit circle in \mathbb{R}^2 , and D^2 denotes the unit disk in \mathbb{R}^2 . Then the inclusion $f: S^1 \hookrightarrow D^2$ is **nullhomotopic**.

Proof. We see this by considering

$$F_t(x) = (1-t)f(x) + (t \cdot 0).$$

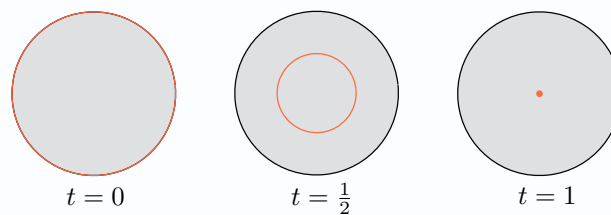


Figure 1.2: The illustration of $F_t(x)$

We see that there is a **homotopy** from $f(x)$ to 0 (the zero map which maps everything to 0), and since 0 is a constant map, hence it's actually a **nullhomotopy**. \otimes

Example. The maps

$$\begin{array}{ccc} S^1 & \rightarrow & S^1 \\ \Theta & \mapsto & S^1 \end{array} \quad \text{and} \quad \begin{array}{ccc} S^1 & \rightarrow & S^1 \\ \Theta & \mapsto & -\Theta \end{array}$$

are **not homotopy**.

Remark. It will essentially **flip** the orientation, hence we can't deform one to another continuously.

Exercise. A subset $S \subseteq \mathbb{R}^n$ is star-shaped if $\exists x_0 \in S$ s.t. $\forall x \in S$, the line from x_0 to x lies in S . Show that $\text{id}: S \rightarrow S$ is **nullhomotopic**.

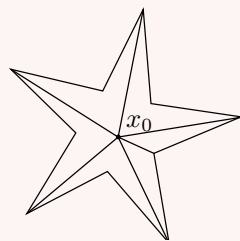


Figure 1.3: Star-shaped illustration

Answer. Consider

$$F_t(x) := (1-t)x + tx_0,$$

which essentially just concentrates all points x to x_0 . *

Exercise. Suppose

$$X \begin{array}{c} \xrightarrow{f_1} \\ \xrightarrow{f_0} \end{array} Y \begin{array}{c} \xrightarrow{g_1} \\ \xrightarrow{g_0} \end{array} Z$$

where

$$f_0 \simeq_{F_t} f_1, \quad g_0 \simeq_{G_t} g_1.$$

Show

$$g_0 \circ f_0 \simeq g_1 \circ f_1.$$

Answer. Consider $I \times X \rightarrow Z$, where

$$\begin{array}{ccccc} X \times I & \rightarrow & Y \times I & \rightarrow & Z \\ (x, t) & \mapsto & (F_t(x), t) & \mapsto & G_t(F_t(x)). \end{array}$$

Remark. Noting that if one wants to be precise, you need to check the continuity of this construction. *

Exercise. How could you show 2 maps are **not** homotopic?

Answer. We'll see! *

Lecture 2: Homotopy Equivalence

As previously seen. Two maps $f, g: X \rightarrow Y$ is homotopy if there exists a map

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$$F_t(x): X \times I \rightarrow Y$$

with the properties

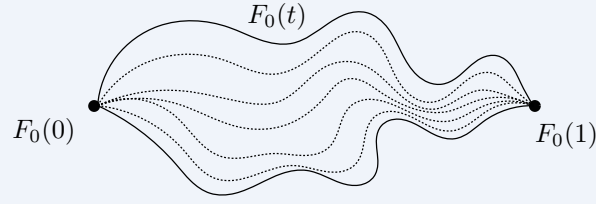
- (1) Continuous
- (2) $F_0(x) = f(x)$
- (3) $F_1(x) = g(x)$

Remark. The continuity of F_t is an even stronger condition for the continuity of F_t for a fixed t .

We now introduce another concept.

Definition 1.1.4 (Homotopy relative). Given two spaces X, Y , and let $B \subseteq X$. Then a homotopy $F_t(x): X \rightarrow Y$ is called *homotopy relative B* (denotes $\text{rel}B$) if $F_t(b)$ is independent of t for all $b \in B$.

Example. Given X and $B = \{0, 1\}$. Then the homotopy of paths from $[0, 1] \rightarrow X$ is $\text{rel}\{0, 1\}$.



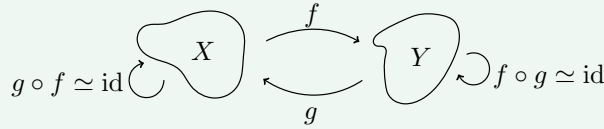
1.2 Homotopy Equivalence

With this, we can introduce the concept of *homotopy equivalence*.

Definition. Let X, Y be topological spaces, and $f: X \rightarrow Y$ being a continuous map.

Definition 1.2.1 (Homotopy equivalence). A map $f: X \rightarrow Y$ is a *homotopy equivalence* if $\exists g: Y \rightarrow X$ such that

$$f \circ g \simeq \text{id}_Y, \quad g \circ f \simeq \text{id}_X.$$



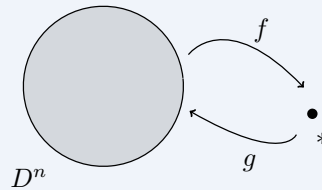
Definition 1.2.2 (Homotopy equivalent). If $f: X \rightarrow Y$ is a *homotopy equivalence*, we then say that X, Y are *homotopy equivalent*.

Definition 1.2.3 (Homotopy inverse). If $f: X \rightarrow Y$ is a *homotopy equivalence* realize with g , then g is called the *homotopy inverse* of f .

Definition 1.2.4 (Homotopy type). If X, Y are *homotopy equivalent*, then we say that they have the same *homotopy type*.

Notation. We denote a closed n -disk as D^n .

Example. D^n is *homotopy equivalent* to a point.



Proof. We see that $f \circ g = \text{id}_*$ and

$$g \circ f = \text{constant map at } \underbrace{0}_{g(*)},$$

which is *homotopic* to id_{D^n} by *straight line homotopy* $F_t(x) = tx$. Specifically, we see that this holds for any convex set. *

Definition 1.2.5 (Contractible). We say that a space X is *contractible* if X is *homotopy equivalent* to a point.

The following proposition is added much after, which may uses some concepts not yet covered.

Proposition 1.2.1. The followings are equivalent.

- (1) X is [contractible](#).
- (2) $\forall x \in X, \text{id}_X \simeq c_x$.
- (3) $\exists x \in X, \text{id}_X \simeq c_x$.

Proof. We see that 2. \Rightarrow 3. is obvious. We consider 3. \Rightarrow 2. This follows from the following general lemma.

Lemma 1.2.1. Given a topological space X such that $\exists x \in X, \text{id}_X \simeq c_x$, with $f, g: Y \rightarrow X$, then $f \simeq g$.

Proof. Let $x \in X$ such that $\text{id}_X \simeq c_x$. Then

$$f = \text{id}_X \circ f \simeq c_x \circ f = c_x \circ g \simeq \text{id}_X \circ g = g.$$

■

Then, from this [Lemma 1.2.1](#), we see that assuming $x_0 \in X$ such that $\text{id}_X \simeq c_{x_0}$, then consider c_x for all $x \in X$, then from [Lemma 1.2.1](#), we see that $c_x \simeq \text{id}_X$.

To show 3. \Rightarrow 1., we let $x_0 \in X$ such that $\text{id}_X \simeq c_{x_0}$.

$$X \begin{array}{c} \xrightarrow{f} \\ \xleftarrow{g} \end{array} \{*\}$$

Since $g(*) = x_0$, and

$$\begin{aligned} g \circ f &: X \rightarrow X \\ x &\mapsto x_0, \end{aligned}$$

which is just c_{x_0} , from the assumption we're done.

Now, we show 1. \Rightarrow 3. Let

$$X \begin{array}{c} \xrightarrow{f} \\ \xleftarrow{g} \end{array} \{*\}$$

be a [homotopy equivalent](#), let $g(*) = x_0$. We see that $c_{x_0} \simeq \text{id}_X$ since

$$g \circ f = c_{x_0} \simeq \text{id}_X.$$

■

Remark. Note that the above notation c_x is introduced [here](#).

Definition. Before doing exercises, we introduce the following new concepts.

Definition 1.2.6 (Retraction). Given $B \subseteq X$, a *retraction* from X to B is a map $f: X \rightarrow X$ (or $X \rightarrow B$) such that $\forall b \in B$ $f(b) = b$, namely $r|_B = \text{id}_B$. Or one can see this from

$$\begin{array}{ccccc} B & \xleftarrow{i} & X & \xrightarrow{r} & B \\ & & \searrow r \circ i & \nearrow & \\ & & & & \end{array}$$

where r is a retraction if and only if $r \circ i = \text{id}_B$, where i is an inclusion identity.

Definition 1.2.7 (Retract). If the above r exists, we say that B is a *retract* of X .

Definition 1.2.8 (Deformation retraction). Given X and $B \subseteq X$, a (strong) deformation retraction $F_t: X \rightarrow X$ onto B is a homotopy $\text{rel} B$ from the id_X to a retraction from X to B . i.e.,

$$\begin{aligned} F_0(x) &= x & \forall x \in X \\ F_1(x) &\in B & \forall x \in X \\ F_t(b) &= b & \forall t \forall b \in B. \end{aligned}$$

Exercise. Let $X \simeq Y$. Show X is path-connected if and only if Y is.

Answer. Suppose X is path-connected. Then we see that given two points x_1 and x_2 in X , there exists a path $\gamma(t)$ with

$$\gamma: [0, 1] \rightarrow X, \quad \gamma(0) = x_1, \quad \gamma(1) = x_2.$$

Since $X \simeq Y$, then there exists a pair of f and g such that $f: X \rightarrow Y$ and $g: Y \rightarrow X$ with

$$f \circ g \underset{F}{\simeq} \text{id}_Y, \quad g \circ f \underset{G}{\simeq} \text{id}_X.$$

(Notice the abuse of notation)

For any two y_1 and $y_2 \in Y$, we want to construct a path $\gamma'(t)$ such that

$$\gamma': [0, 1] \rightarrow Y, \quad \gamma'(0) = y_1, \quad \gamma'(1) = y_2.$$

Firstly, we let $g(y_1) =: x_1$ and $g(y_2) =: x_2$. From the argument above, we know there exists such a γ starting at $x_1 = g(y_1)$ ending at $x_2 = g(y_2)$. Now, consider $f(\gamma(t)) = (f \circ \gamma)(t)$ such that

$$f \circ \gamma: I \rightarrow Y, \quad f \circ \gamma(0) = y'_1, \quad f \circ \gamma(1) = y'_2,$$

we immediately see that y'_1 and y'_2 is path connected. Now, we claim that y_1 and y'_1 are path connected in Y , hence so are y_2 and y'_2 . To see this, note that

$$f \circ g \underset{F}{\simeq} \text{id}_Y,$$

which means that there exists $F: Y \times I \rightarrow Y$ such that

$$\begin{cases} F(y_1, 0) = f \circ g(y_1) = f(x_1) = f(\gamma(0)) = (f \circ \gamma)(0) = y'_1 \\ F(y_1, 1) = \text{id}_Y(y_1) = y_1. \end{cases}$$

Since F is continuous in I , we see that there must exist a path connects y_1 and y'_1 . The same argument applies to y_2 and y'_2 . Now, we see that the path

$$y_1 \rightarrow y'_1 \rightarrow y'_2 \rightarrow y_2$$

is a path in Y for any two y_1 and y_2 , which shows Y is path-connected.

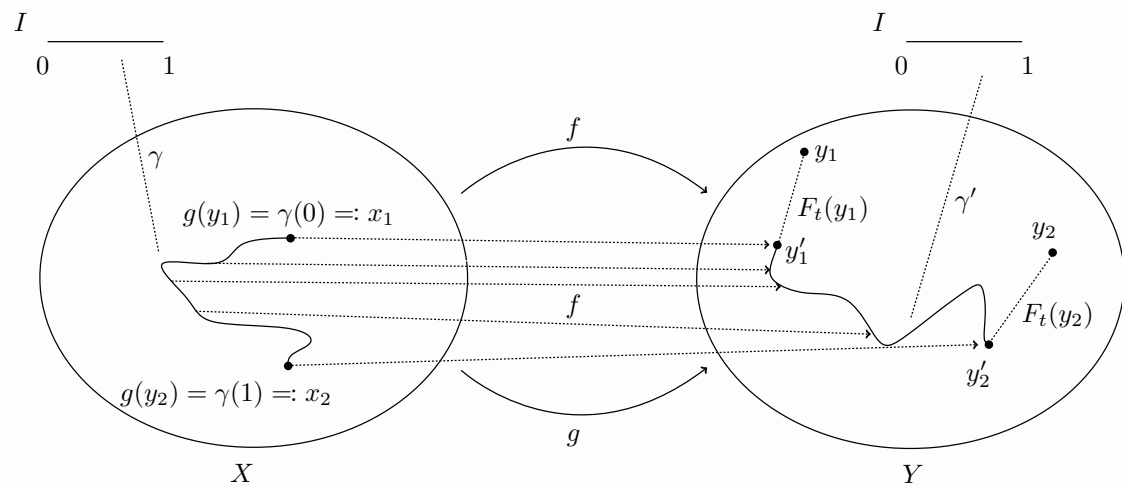


Figure 1.4: Demonstration of the proof.

Challenge: One can further show that the connectedness is also preserved by any [homotopy equivalence](#). *

Corollary 1.2.1. A [contractible](#) space is [path-connected](#).

Exercise. Show that if there exists [deformation retraction](#) from X to $B \subseteq X$, then $X \simeq B$.

Lecture 3: Deformation Retraction

As previously seen. A [deformation retraction](#) is a [homotopy](#) of maps $\text{rel} B \ X \rightarrow X$ from id_X to a [retraction](#) from X to B . Then B is a [deformation retract](#).

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Example. S^1 is a [deformation retraction](#) of $D^2 \setminus \{0\}$.

Proof. Indeed, since

$$F_t(x) = t \cdot \frac{x}{\|x\|} + (1-t)x.$$

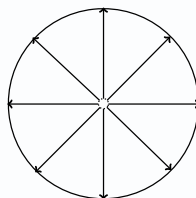


Figure 1.5: The [deformation retraction](#) of $D^2 \setminus \{0\}$ is just to *enlarge* that hole and push all the interior of D^2 to the boundary, which is S^1 .

*

Example. \mathbb{R}^n deformation retracts to 0.

Proof. Indeed, since

$$F_t(x) = (1 - t)x.$$

Remark. This implies that $\mathbb{R}^n \simeq *$, hence we see that

- dimension
- compactness
- etc.

are **not** homotopy invariants.

*

Example. S^1 is a deformation retract of a cylinder and a Möbius band.

Proof. For a cylinder, consider $X \times I \rightarrow X$. Define homotopy on a closed rectangle, then verify it induces map on quotient.

For a Möbius band, we define a homotopy on a closed rectangle, then verify that it respects the equivalence relation.

Finally, we use the universal property of quotient topology to argue that we get a homotopy on Möbius band.

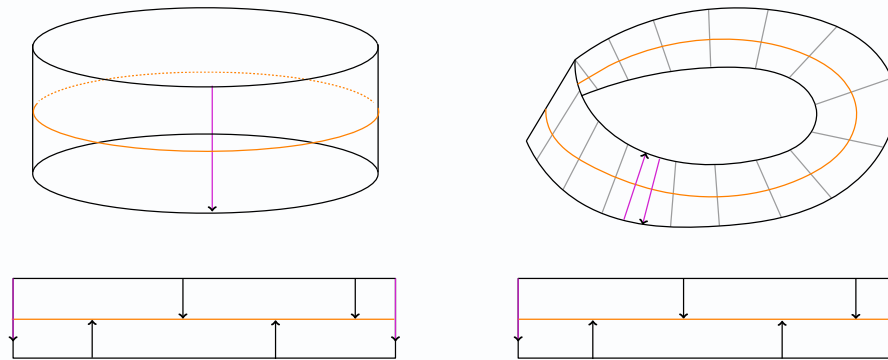


Figure 1.6: The deformation retraction for Cylinder and Möbius band

Remark. We see that Möbius band $\simeq S^1 \simeq$ cylinder, hence the orientability is **not** homotopy invariant.

*

Lecture 4: Cell Complex (CW Complex)

As previously seen. We saw that

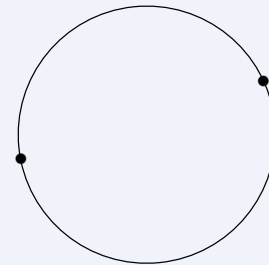
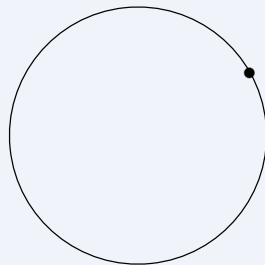
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- homotopy equivalence
- homotopy invariants
 - path-connectedness
- not invariant
 - dimension
 - orientability
 - compactness

1.3 CW Complexes

Example (Constructing spheres). We now see how to construct S^1 and S^2 from ground up.

- S^1 (up to homeomorphism^a)



- S^2
 - glue boundary of 2-disk to a point
 - glue 2 disks onto a circle

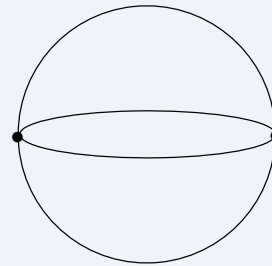
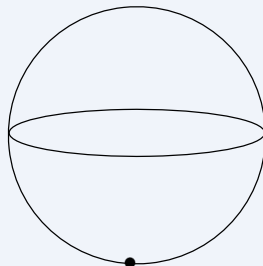
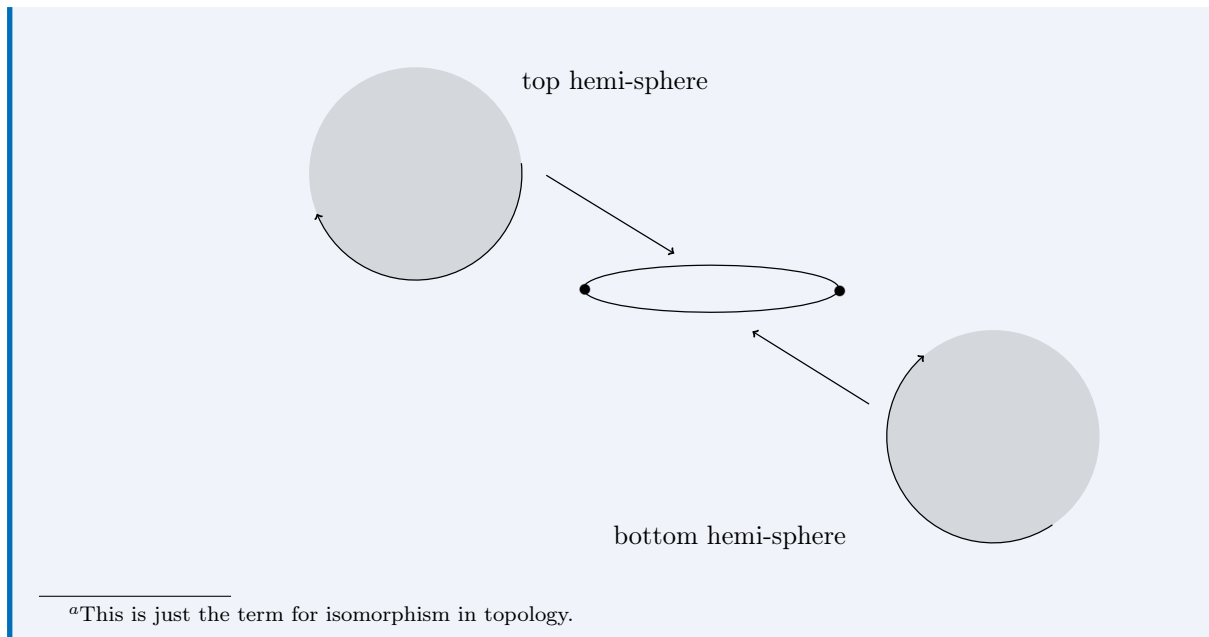
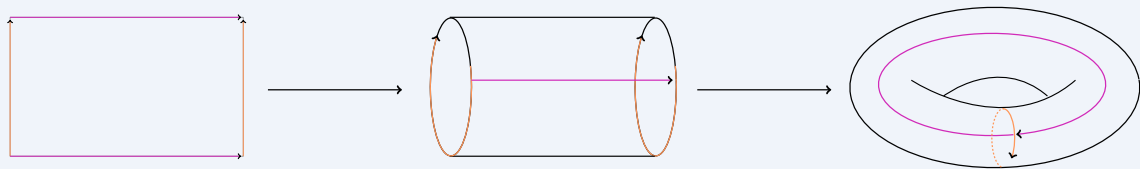


Figure 1.7: **Left:** Glue a 2-disk to a point along its boundary. **Right:** Glue 2 disks to S^1 .

The gluing instruction to construct S^2 in the right-hand side can be demonstrated as follows.



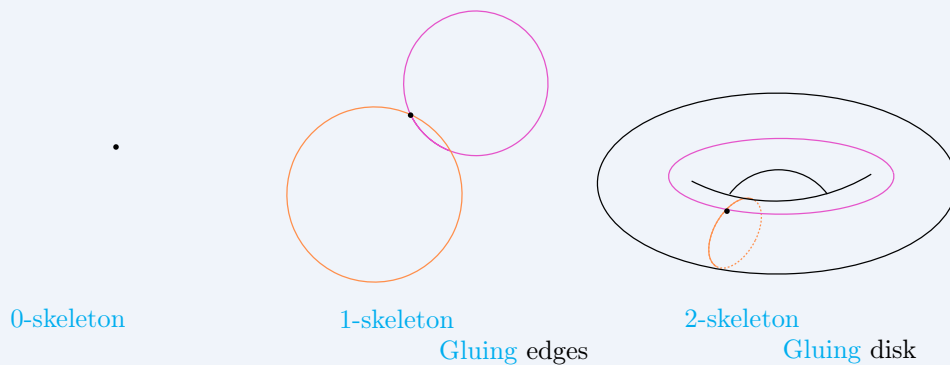
Example (Constructing torus). A torus T is just $T = S^1 \times S^1$.



view as gluing instructions

vertex + 2 edges + 2-disks.

Soon, we'll see that above is just



Notation. Let D^n denotes a closed n -disk (or n -ball) $D^n \simeq \{x \in \mathbb{R}^n : \|x\| \leq 1\}$, and let S^n denotes an n -sphere $S^n \simeq \{x \in \mathbb{R}^{n+1} : \|x\| = 1\}$.

Then, formally, we have the following definition.

Definition 1.3.1 (CW Complex). A *CW Complex* X is a topological space constructed inductively as follows. First, we have the basic elements called **cells**.

Definition 1.3.2 (Cell). We call a point as a *0-cell*, and the interior of D^n $\text{Int}(D^n)$ for $n \geq 1$ as an *n -cell*.

Then, we use **cells** to build our **skeletons**.

Definition 1.3.3 (Skeleton). The 0-skeleton X^0 is a set of discrete points, i.e, 0-cell.

We inductively construct the n -skeleton X^n from X^{n-1} by attaching n -cells e_α^n , where α is the index. Specifically, we follow the gluing instructions called **attaching maps** defined below and obtain X^n from X^{n-1} by

$$X^n = \left(X^{n-1} \coprod_{\alpha} D_{\alpha}^n \right) / x \sim \varphi_{\alpha}(x)$$

with identification $x \sim \varphi_{\alpha}(x)$ for all $x \in \partial D_{\alpha}^n$ with quotient topology.

Remark. We write $X^{(n)}$ for n -skeleton if we need to distinguish from the Cartesian product.

Definition 1.3.4 (Attaching map). The *attaching map* for every cell e_{α}^n is a continuous map φ_{α} such that

$$\varphi_{\alpha}: \partial D_{\alpha}^n \rightarrow X^{n-1}.$$

Finally, we let X be defined as

$$X = \bigcup_{n=0} X^n,$$

equipped with the so-called **weak topology** defined below.

Definition 1.3.5 (Weak topology). The *weak topology*, denoted as \bar{w} , contains open set u such that

$$u \subseteq X \text{ is open} \Leftrightarrow \forall n \ u \cap X^n \text{ is open}.$$

If all **cells** have dimension less than N and there exists an **N -cell**, then $X = X^N$ and we call it *N -dimensional CW complex*.

Example. Let's look at some examples.

- (1) 0-dim **CW complex** is a discrete space.
- (2) 1-dim **CW complex** is a graph.
- (3) A **CW complex** X is finite if it has finitely many **cells**.

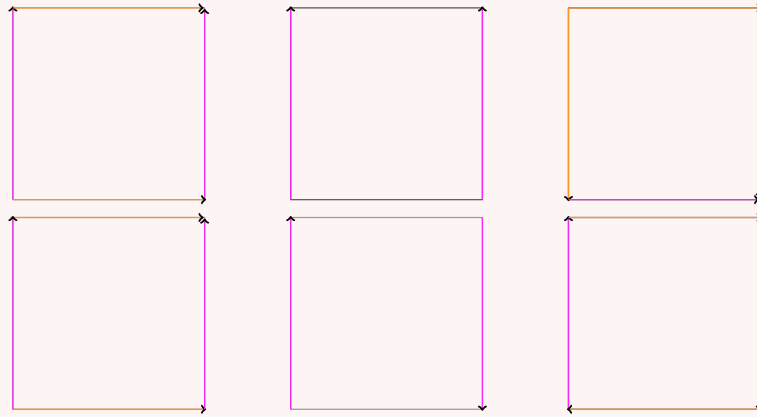
Definition 1.3.6 (CW subcomplex). A *CW subcomplex* $A \subseteq X$ is a closed subset equal to a union of **cells**

$$e_{\alpha}^n = \text{Int}(D_{\alpha}^n).$$

Remark. This inherits a **CW complex** structure.

Exercise. Given the following gluing instruction:

Check the images of **attaching maps**.



identify Torus, Klein bottle, Cylinder, Möbius band, 2-sphere, $\mathbb{R}P$.

Notation. Notice that we call the real projection space as $\mathbb{R}P$, and we also have so-called complex projection space, denote as $\mathbb{C}P$.

Answer. We see that

1. Torus
2. Cylinder
3. 2-sphere
4. Klein bottle
5. Möbius band
6. $\mathbb{R}P$

⊗

Lecture 5: Operation on Spaces

1.4 Operations on CW Complexes

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1.4.1 Products

We can consider the product of two CW complex given by a CW complex structure. Namely, given X and Y two CW complexes, we can take two cells e_α^n from X and e_β^m from Y and form the product space $e_\alpha^n \times e_\beta^m$, which is homeomorphic to an $(n+m)$ -cell. We then take these products as the cells for $X \times Y$. Specifically, given X, Y are CW complexes, then $X \times Y$ has a cells structure

$$\{e_\alpha^m \times e_\alpha^n : e_\alpha^m \text{ is an } m\text{-cell on } X, e_\alpha^n \text{ is an } n\text{-cell on } Y\}.$$

Remark. The product topology may not agree with the weak topology on the $X \times Y$. However, they do agree if X or Y is locally compact or if X and Y both have at most countably many cells.

1.4.2 Wedge Sum

Given X, Y are CW complexes, and $x_0 \in X^0, y_0 \in Y^0$ (only points). Then we define $X \vee Y = X \amalg Y$ with quotient topology.

Remark. $X \vee Y$ is a CW complex.

1.4.3 Quotients

Let X be a **CW complex**, and $A \subseteq X$ **subcomplex** (closed union of **cells**), then X / A is a quotient space collapse A to one point and inherits a **CW complex** structure.

Remark. X / A is a **CW complex**.

Proof. With the **0-skeleton** being

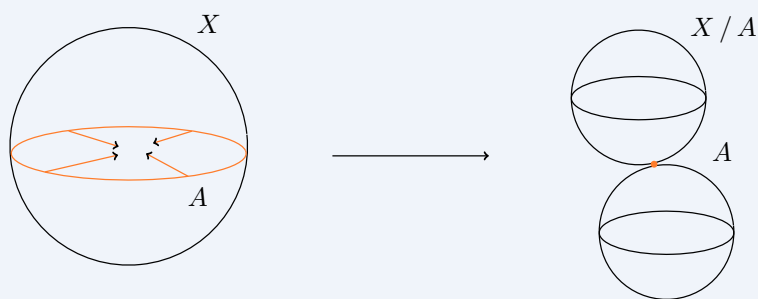
$$(X^0 - A^0) \coprod *$$

where $*$ is a point for A , then each **cell** of $X - A$ is attached to $(X / A)^n$ by **attaching map**

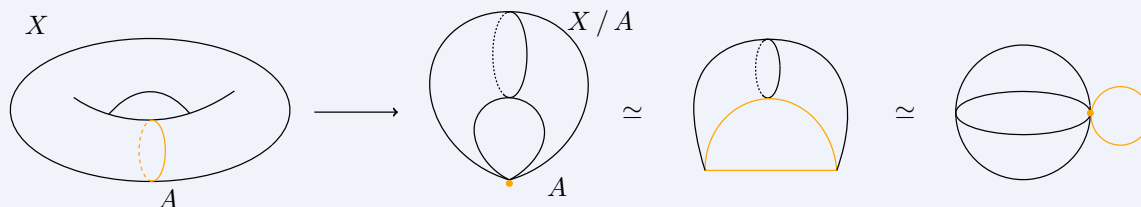
$$S^n \xrightarrow{\phi_\alpha} X^n \xrightarrow{\text{quotient}} X^n / A^n$$

⊗

Example. We can take the sphere and squish the equator down to form a **wedge** of two spheres.



Example. We can take the torus and squish down a ring around the hole.



We see that X / A is **homotopy equivalent** to a 2-sphere **wedged** with a 1-sphere via extending the orange point into a line, and then sliding the left point to the line along the 2-sphere towards the other points, forming a circle.

Chapter 2

Category Theory

Category theory is a general theory of mathematical structures and their relations introduced in the middle of the 20th century along with the development of algebraic topology. Nowadays, category theory is used in almost all areas of mathematics, and in some areas of computer science. In particular, many constructions of new mathematical objects from previous ones, that appear similarly in several contexts are conveniently expressed and unified in terms of categories. Hence, we now study this in depth and will use it heavily afterwards.

Lecture 6: A Foray into Category Theory

2.1 Category Theory

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When discussing algebraic-related topics, category theory is an essential tool doing this. It exploits some internal structure of objects we care about, such as [fundamental group](#), [homology group](#) and so on, as we'll see.

Now, we see start with the definition.

Definition 2.1.1 (Category). A *category* \mathcal{C} is 3 pieces of data

- A class of [objects](#) $\text{Ob}(\mathcal{C})$.

Definition 2.1.2 (Object). An *object* in a [category](#) can be realized as a node in a directed diagram.

- $\forall X, Y \in \text{Ob}(\mathcal{C})$ a class of [morphisms](#) or arrows, $\text{Hom}_{\mathcal{C}}(X, Y)$.

Definition 2.1.3 (Morphism). A *morphism* in a [category](#) is just an arrow between [objects](#).

- $\forall X, Y, Z \in \text{Ob}(\mathcal{C})$, there exists a composition law

$$\text{Hom}(X, Y) \times \text{Hom}(Y, Z) \rightarrow \text{Hom}(X, Z), \quad (f, g) \mapsto g \circ f.$$

and 2 axioms

- Associativity. $(f \circ g) \circ h = f \circ (g \circ h)$ for all [morphisms](#) f, g, h where composites are defined.
- Identity. $\forall X \in \text{Ob}(\mathcal{C}) \exists \text{id}_X \in \text{Hom}_{\mathcal{C}}(X, X)$ such that

$$f \circ \text{id}_X = f, \quad \text{id}_X \circ g = g$$

for all f, g where this makes sense.

Example. We introduce some common [category](#).

\mathcal{C}	$\text{Ob}(\mathcal{C})$	$\text{Mor}(\mathcal{C})$
$\underline{\text{set}}$	Sets X	All maps of sets
$\underline{\text{fset}}$	Finite sets	All maps
$\underline{\text{Gp}}$	Groups	Group Homomorphisms
$\underline{\text{Ab}}$	Abelian groups	Group Homomorphisms
$\underline{k\text{-vect}}$	Vector spaces over k	k -linear maps
$\underline{\text{Rng}}$	Rings	Ring Homomorphisms
$\underline{\text{Top}}$	Topological spaces	Continuous maps
$\underline{\text{Haus}}$	Hausdorff Spaces	Continuous maps
$\underline{\text{hTop}}$	Topological spaces	Homotopy classes of continuous maps
$\underline{\text{Top}}^*$	Based topological spaces ^a	Based maps ^b

^aTopological spaces with a distinguished base point $x_0 \in X$

^bContinuous maps that preserve base point $f: (X, x_0) \rightarrow (Y, y_0)$ such that $f: X \rightarrow Y$, $f(x_0) = y_0$ is continuous.

Remark. From [Definition 2.1.1](#), we see that a [category](#) is just any **directed diagram** plus composition law and identities.

$$\text{id}_A \curvearrowright A \longrightarrow B \curvearrowleft \text{id}_B.$$

Definition. Given a [morphism](#) $f: M \rightarrow N$, then we have the following definitions.

Definition 2.1.4 (Monic). f is *monic* if

$$\forall g_1, g_2 \quad f \circ g_1 = f \circ g_2 \Rightarrow g_1 = g_2.$$

$$A \begin{array}{c} \xrightarrow{g_1} \\ \xrightarrow{g_2} \end{array} M \xrightarrow{f} N$$

Definition 2.1.5 (Epic). Dually, f is *epic* if

$$\forall g_1, g_2 \quad g_1 \circ f = g_2 \circ f \Rightarrow g_1 = g_2.$$

$$M \xrightarrow{f} N \begin{array}{c} \xrightarrow{g_1} \\ \xrightarrow{g_2} \end{array} B$$

Lemma 2.1.1. In $\underline{\text{set}}, \underline{\text{Ab}}, \underline{\text{Top}}, \underline{\text{Gp}}$, a map is [monic](#) if and only if f is injective, and [epic](#) if and only if f is surjective.

Proof. In $\underline{\text{set}}$, we prove that f is [monic](#) if and only if f is injective. Suppose $f \circ g_1 = f \circ g_2$ and f is injective, then for any a ,

$$f(g_1(a)) = f(g_2(a)) \Rightarrow g_1(a) = g_2(a),$$

hence $g_1 = g_2$.

Now we prove another direction, with contrapositive. Namely, we assume that f is **not** injective and show that f is not [monic](#). Suppose $f(a) = f(b)$ and $a \neq b$, we want to show such g_i exists. This is easy by considering

$$g_1: * \mapsto a, \quad g_2: * \mapsto b.$$

■

2.1.1 Functor

After introducing the [category](#), we then see the most important concept we'll use, a [functor](#). Again, we start with the definition.

Definition 2.1.6 (Functor). Given \mathcal{C}, \mathcal{D} be two [categories](#). A (covariant) functor $F: \mathcal{C} \rightarrow \mathcal{D}$ is

- (1) a map on [objects](#)

$$\begin{aligned} F: \text{Ob}(\mathcal{C}) &\rightarrow \text{Ob}(\mathcal{D}) \\ X &\mapsto F(X). \end{aligned}$$

- (2) maps of [morphisms](#)

$$\begin{aligned} \text{Hom}_{\mathcal{C}}(X, Y) &\rightarrow \text{Hom}_{\mathcal{D}}(F(X), F(Y)) \\ [f: X \rightarrow Y] &\mapsto [F(f): F(X) \rightarrow F(Y)] \end{aligned}$$

such that

- $F(\text{id}_X) = \text{id}_{F(X)}$
- $F(f \circ g) = F(f) \circ F(g)$

Lecture 7: Functors

Example (Applying a covariant functor). Assume that we initially have a commutative diagram in \mathcal{C} as

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ & \searrow g \circ f & \downarrow g \\ & & Z \end{array}$$

and a [functor](#) $F: \mathcal{C} \rightarrow \mathcal{D}$. After applying F , we'll have

$$\begin{array}{ccc} F(X) & \xrightarrow{F(f)} & F(Y) \\ & \searrow F(g \circ f) = F(g) \circ F(f) & \downarrow F(g) \\ & & F(Z) \end{array}$$

which is a commutative diagram in \mathcal{D} .

We can also have a so-called [contravariant functor](#).

Definition 2.1.7 (Contravariant functor). Given \mathcal{C}, \mathcal{D} be two [categories](#). A *contravariant functor* $F: \mathcal{C} \rightarrow \mathcal{D}$ is

- (1) a map on [objects](#)

$$\begin{aligned} F: \text{Ob}(\mathcal{C}) &\rightarrow \text{Ob}(\mathcal{D}) \\ X &\mapsto F(X). \end{aligned}$$

- (2) maps of [morphisms](#)

$$\begin{aligned} \text{Hom}_{\mathcal{C}}(X, Y) &\rightarrow \text{Hom}_{\mathcal{D}}(F(Y), F(X)) \\ [f: X \rightarrow Y] &\mapsto [F(f): F(Y) \rightarrow F(X)] \end{aligned}$$

such that

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- $F(\text{id}_X) = \text{id}_{F(X)}$
- $F(f \circ g) = F(f) \circ F(g)$

Example (Applying a contravariant functor). Then, we see that in this case, when we apply a **contravariant functor** F , the diagram becomes

$$\begin{array}{ccc} F(X) & \xleftarrow{F(f)} & F(Y) \\ & \nwarrow & \uparrow F(g) \\ & & F(Z) \end{array}$$

$F(g \circ f) = F(f) \circ F(g)$

which is a commutative diagram in \mathcal{D} .

We now see some common **functors** as examples.

Example (Identity functor). Define I as $I: \mathcal{C} \rightarrow \mathcal{C}$ such that it just send an object $C \in \mathcal{C}$ to itself.

Example (Forgetful functor). We see two examples.

- Define F as $F: \underline{\text{Gp}} \rightarrow \underline{\text{set}}$ such that $G \mapsto G$.^a Specifically,

$$[f: G \rightarrow H] \mapsto [f: G \rightarrow H].$$

- Define F as $F: \underline{\text{Top}} \rightarrow \underline{\text{set}}$ such that $X \mapsto X$.^b Specifically,

$$[f: X \rightarrow Y] \mapsto [f: X \rightarrow Y].$$

^a G is now just the underlying set of the group G .

^b X is now just the underlying set of the topological space X .

Example (Free functor). Define a **functor** as

$$\begin{aligned} \underline{\text{set}} &\rightarrow k\text{-vect} \\ s &\mapsto \text{"free" } k\text{-vector space on } s \end{aligned}$$

i.e., vector space with basis s such that

$$[f: A \rightarrow B] \mapsto [\text{unique } k\text{-linear map extending } f]$$

Example. Let T be defined as

$$\begin{aligned} T: k\text{-vect} &\rightarrow k\text{-vect} \\ V &\mapsto V^* = \text{Hom}_k(V, k). \end{aligned}$$

If we are working on a basis, we can then represent T as a matrix A , and we further have

$$A \mapsto A^\top.$$

Remark. Specifically, we care about two **functors**.

- (1) $\pi_1: \underline{\text{Top}}^* \rightarrow \underline{\text{Gp}}$ such that

$$\begin{aligned} \pi_1: \underline{\text{Top}}^* &\rightarrow \underline{\text{Gp}} \\ (X, x_0) &\mapsto \pi_1(X, x_0), \end{aligned}$$

where π_1 is the so-called **fundamental group**.

(2) $H_p: \underline{\text{Top}} \rightarrow \underline{\text{Ab}}$ such that

$$\begin{aligned} H_p: \underline{\text{Top}} &\rightarrow \underline{\text{Ab}} \\ X &\mapsto H_p(X), \end{aligned}$$

where H_p is the so-called p^{th} **homology group**.

We are not building toward **fundamental groups**.

Let's see some building blocks we need.

2.2 Free Groups

Definition 2.2.1 (Free group). Given a set S , the *free group* is a group F_S on S with a map $S \rightarrow F_S$ satisfying the following universal property: If G is any group, $f: S \rightarrow G$ is any map of sets, f extends uniquely to group homomorphism $\bar{f}: F_S \rightarrow G$.

$$\begin{array}{ccc} S & \longrightarrow & F_S \\ & \searrow f & \downarrow \exists! \bar{f}: \text{group homomorphism} \\ & & G \end{array}$$

Note. This defines a *natural bijection*

$$\text{Hom}_{\underline{\text{set}}}(S, \mathcal{U}(G)) \cong \text{Hom}_{\underline{\text{Grp}}}(F_S, G),$$

where $\mathcal{U}(G)$ is the **forgetful functor** from the **category** of groups to the **category** of sets. This is the statement that the **free functor** and the **forgetful functor** are **adjoint**; specifically that the **free functor** is the left **adjoint** (appears on the left in the Hom above).

Definition 2.2.2 (Adjoint functor). A **free** and **forgetful functor** is *adjoints*.

Remark. Whenever we state a universal property for an **object** (plus a map), an **object** (plus a map) may or may not exist. If such **object** exists, then it defines the **object uniquely up to unique isomorphism**, so we can use the universal property as the *definition* of the **object** (plus a map).

Lemma 2.2.1. Universal property defines F_S (plus a map $S \rightarrow F(S)$) uniquely up to unique isomorphism.

Proof. Fix S . Suppose

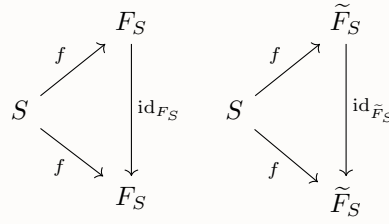
$$S \rightarrow F_S, \quad S \rightarrow \tilde{F}_S$$

both satisfy the unique property. By universal property, there exist maps such that

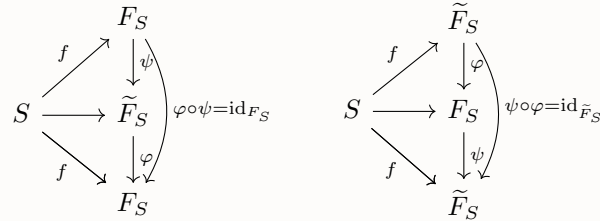
$$\begin{array}{ccc} S & \longrightarrow & \tilde{F}_S \\ & \searrow f & \downarrow \exists! \varphi \\ & & F_S \end{array} \qquad \begin{array}{ccc} S & \longrightarrow & F_S \\ & \searrow f & \downarrow \exists! \psi \\ & & \tilde{F}_S \end{array}$$

We'll show φ and ψ are inverses (and the unique isomorphism making above commute). Since

we must have the following two commutative graphs.



Hence, we see that



where the identity makes these outer triangles commute, then by the uniqueness in universal property, we must have

$$\varphi \circ \psi = \text{id}_{F_S}, \quad \psi \circ \varphi = \text{id}_{\tilde{F}_S},$$

so φ and ψ are inverses (thus group isomorphism). ■

Lecture 8: The Fundamental Group π_1

Example. In [category \$\mathbf{Ab}\$](#) [free Abelian group](#) on a set S is

$$\bigoplus_S \mathbb{Z}.$$

In [category](#) of fields, no such thing as [free field](#) on S .

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2.2.1 Constructing the Free Groups F_S

Proposition 2.2.1. The [free group](#) defined by the universal property exists.

Proof. We'll just give a construction below. First, we see the definition.

Definition 2.2.3 (Word). Fix a set S , and we define a *word* as a finite sequence (possibly \emptyset) in the formal symbols

$$\{s, s^{-1} \mid s \in S\}.$$

Then we see that elements in F_S are equivalence classes of [words](#) with the equivalence relation being

- deleted ss^{-1} or $s^{-1}s$. i.e.,

$$vs^{-1}sw \sim vw$$

$$vss^{-1}w \sim vw$$

for every [word](#) $v, w, s \in S$,

with the group operation being concatenation.

Example. Given words ab^{-1}, bba , their product is

$$ab^{-1} \cdot bba = ab^{-1}bba = aba.$$

Exercise. There are something left to check.

- (1) This product is well-defined on equivalence classes.
- (2) Every equivalence class of words has a unique *reduced form*, namely the representation.
- (3) Check that F_S satisfies the universal property with respect to the map

$$S \rightarrow F_S, \quad s \mapsto s.$$



Chapter 3

The Fundamental Group

The **fundamental group** is the first and the simplest **homotopy** group, which records information about the basic shape, or holes, of the topological space. Not surprisingly, this is already interesting enough to study and can help us distinguish between different shapes just by finding the spaces' corresponding **fundamental groups**.

3.1 Path

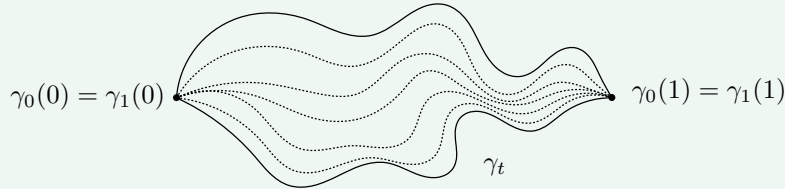
We start with the definition.

Definition 3.1.1 (Path). A *path* in a space X is a continuous map

$$\gamma: I \rightarrow X$$

where $I = [0, 1]$.

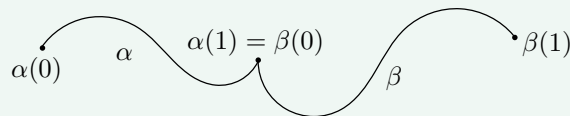
Definition 3.1.2 (Homotopy path). A *homotopy of paths* γ_0, γ_1 is a **homotopy** from γ_0 to $\gamma_1 \text{ rel}\{0, 1\}$.



Example. Fix $x_1, x_0 \in X$, then \exists **homotopy** of **paths** is an equivalence relation on **paths** from x_0 to x_1 (i.e., γ with $\gamma(0) = x_0, \gamma(1) = x_1$).

Definition 3.1.3 (Path composition). For **paths** α, β in X with $\alpha(1) = \beta(0)$, the *composition*^a $\alpha \cdot \beta$ is

$$(\alpha \cdot \beta)(t) := \begin{cases} \alpha(2t), & \text{if } t \in \left[0, \frac{1}{2}\right] \\ \beta(2t - 1), & \text{if } t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$



^aAlso named *product*, *concatenation*.

Remark. By the pasting lemma, this is continuous, hence $\alpha \cdot \beta$ is actually a **path** from $\alpha(0)$ to $\beta(1)$.

Definition 3.1.4 (Reparameterization). Let $\gamma: I \rightarrow X$ be a **path**, then a *reparameterization* of γ is a **path**

$$\gamma': I \xrightarrow{\varphi} I \xrightarrow{\gamma} X$$

where φ is continuous and

$$\varphi(0) = 0, \quad \varphi(1) = 1.$$

Exercise. A **path** γ is **homotopic rel** $\{0, 1\}$ to all of its **reparameterizations**.

Answer. We show that γ and $\gamma \circ \phi$ are **homotopic rel** $\{0, 1\}$ by showing that there exists a continuous F_t such that

$$F_0 = \gamma, \quad F_1 = \gamma \circ \phi.$$

Notice that since ϕ is continuous, so we define

$$F_t(x) = (1-t)\gamma(x) + t \cdot \gamma \circ \phi(x).$$

We see that

$$F_0(x) = \gamma(x), \quad F_1(x) = \gamma \circ \phi(x),$$

and also, we have

$$F_t(x) \in X$$

for all $x, t \in I$.

Now, we check that F_t really gives us a **homotopic rel** $\{0, 1\}$. We have

$$\begin{aligned} F_t(0) &= (1-t)\gamma(0) + t \cdot \gamma \circ \phi(0) = (1-t)\gamma(0) + t \cdot \underbrace{\gamma(\phi(0))}_0 = \gamma(0), \\ F_t(1) &= (1-t)\gamma(1) + t \cdot \gamma \circ \phi(1) = (1-t)\gamma(1) + t \cdot \underbrace{\gamma(\phi(1))}_1 = \gamma(1), \end{aligned}$$

which shows that 0 and 1 are independent of t , hence γ and $\gamma \circ \phi$ are **homotopic rel** $\{0, 1\}$. \circledast

Exercise. Fix $x_1, x_1 \in X$. Then **homotopy of paths** (**relative** $\{0, 1\}$) is an equivalence relation on **paths** from x_0 to x_1 .

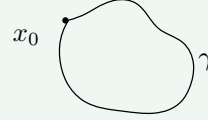
3.2 Fundamental Group and Groupoid

In class, we only discuss **fundamental groups**. But there is an also important concept called **fundamental groupoid**, which is kind of similar but more general and power to use. I include this just for completeness, feel free to skip the additional content. Now, let's start with **fundamental group**.

3.2.1 Fundamental Group

Definition 3.2.1 (Fundamental group). Let X denotes the space and let $x_0 \in X$ be the base point. The *fundamental group of X based at x_0* , denoted by $\pi_1(X, x_0)$, is a group such that

- Elements: **Homotopy** classes **rel** $\{0, 1\}$ of **paths** $[\gamma]$ where γ is a **loop** with $\gamma(0) = \gamma(1) = x_0$ ^a

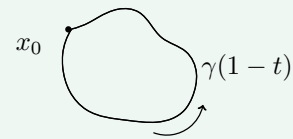
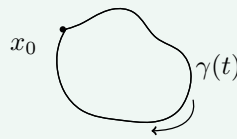


- Operation: [Composition of paths](#).
- Identity: Constant loop γ based at x_0 such that

$$\gamma: I \rightarrow X, \quad t \mapsto x_0$$

- Inverses: The inverse $[\gamma]^{-1}$ of $[\gamma]$ is represented by the loop $\bar{\gamma}$ such that

$$\bar{\gamma}(t) = \gamma(1 - t).$$



^aWe say γ is **based** at x_0 .

Proof. We actually need to prove that the defined π_1 actually is a group, hence, we prove that

Associativity. $[\gamma_1 \cdot (\gamma_2 \cdot \gamma_3)] = [(\gamma_1 \cdot \gamma_2) \cdot \gamma_3]$. We break this down into

$$\gamma_1 \cdot (\gamma_2 \cdot \gamma_3)(t) = \begin{cases} \gamma_1(2t), & t \in \left[0, \frac{1}{2}\right]; \\ (\gamma_2 \cdot \gamma_3)(2t - 1), & t \in \left[\frac{1}{2}, 1\right] \end{cases} = \begin{cases} \gamma_1(2t), & t \in \left[0, \frac{1}{2}\right]; \\ \gamma_2(4t - 2), & t \in \left[\frac{1}{2}, \frac{3}{4}\right]; \\ \gamma_3(4t - 3), & t \in \left[\frac{3}{4}, 1\right], \end{cases}$$

and

$$(\gamma_1 \cdot \gamma_2) \cdot \gamma_3(t) = \begin{cases} (\gamma_1 \cdot \gamma_2)(2t), & t \in \left[0, \frac{1}{2}\right]; \\ \gamma_3(2t - 1), & t \in \left[\frac{1}{2}, 1\right] \end{cases} = \begin{cases} \gamma_1(4t), & t \in \left[0, \frac{1}{4}\right]; \\ \gamma_2(4t - 1), & t \in \left[\frac{1}{4}, \frac{1}{2}\right]; \\ \gamma_3(2t - 1), & t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

Then, we define $\phi: I \rightarrow I$ such that

$$\phi(t) = \begin{cases} 2t \in \left[0, \frac{1}{2}\right], & t \in \left[0, \frac{1}{4}\right]; \\ t + \frac{1}{4} \in \left[\frac{1}{2}, \frac{3}{4}\right], & t \in \left[\frac{1}{4}, \frac{1}{2}\right]; \\ \frac{t+1}{2} \in \left[\frac{3}{4}, 1\right], & t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

We easily see that

$$\gamma_1 \cdot (\gamma_2 \cdot \gamma_3)(t) = (\gamma_1 \cdot \gamma_2) \cdot \gamma_3 \circ \phi(t)$$

and $\phi(t)$ is continuous and satisfied $\phi(0) = 0$ and $\phi(1) = 1$, which implies that the associativity holds.

Identity. We want to show that $[\gamma \cdot c] = [\gamma]$. Again, we consider

$$(\gamma \cdot c)(t) = \begin{cases} \gamma(2t), & t \in \left[0, \frac{1}{2}\right]; \\ c(2t-1) = c = x_0 = \gamma(0), & t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

Now, consider $\phi: I \rightarrow I$ such that

$$\phi(t) = \begin{cases} 2t, & t \in \left[0, \frac{1}{2}\right]; \\ 1, & t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

We easily see that

$$(\gamma \cdot c)(t) = (\gamma \circ \phi)(t)$$

and $\phi(t)$ is continuous and satisfied $\phi(0) = 0$ and $\phi(1) = 1$.

Inverses. We want to show that $\gamma \cdot \bar{\gamma} \simeq c$, where $\bar{\gamma}(t) = \gamma(1-t)$. Firstly, we have

$$(\gamma \cdot \bar{\gamma})(t) = \begin{cases} \gamma(2t), & t \in \left[0, \frac{1}{2}\right]; \\ \bar{\gamma}(1-2t), & t \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

We consider F_t given by

$$F_t(x) = \begin{cases} \gamma(2xt), & x \in \left[0, \frac{1}{2}\right]; \\ \bar{\gamma}(1-2xt), & x \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

If $t = 0$, we have

$$F_0(x) = \begin{cases} \gamma(0), & x \in \left[0, \frac{1}{2}\right]; \\ \bar{\gamma}(1), & x \in \left[\frac{1}{2}, 1\right] \end{cases} = x_0$$

for all $x \in I$, namely $F_0 = c$, while when $t = 1$, we have

$$F_1(x) = \begin{cases} \gamma(2x), & x \in \left[0, \frac{1}{2}\right]; \\ \bar{\gamma}(1-2x), & x \in \left[\frac{1}{2}, 1\right] \end{cases} = (\gamma \cdot \bar{\gamma})(x),$$

and we see that F_t is continuous since at $x = \frac{1}{2}$, we have

$$\gamma(2x) = \gamma(1) = \bar{\gamma}(0) = \bar{\gamma}(1-2x),$$

hence we see that F_t is the [homotopy](#) between $\gamma \cdot \bar{\gamma}$ and c .

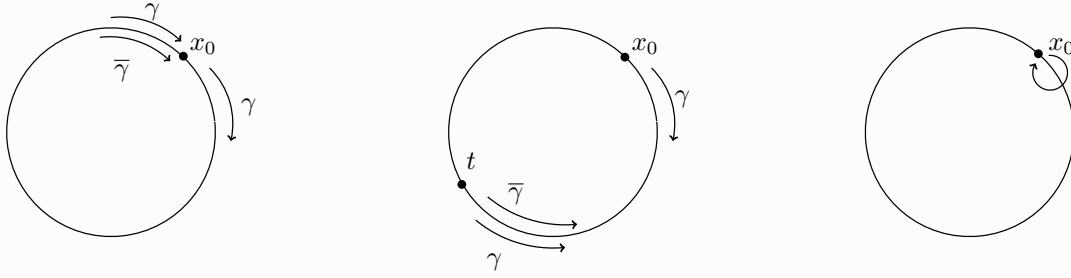


Figure 3.1: Illustration of F_t . Intuitively, the path $\gamma \cdot \bar{\gamma}$ is $x_0 \xrightarrow{\gamma} x_0 \xrightarrow{\bar{\gamma}} x_0$. But now, F_t is $x_0 \xrightarrow{\gamma} t \xrightarrow{\bar{\gamma}} x_0$. We can think of this homotopy as *pulling back* the turning point along the original path.

Theorem 3.2.1. If X is path-connected, then

$$\forall x_0, x_1 \in X \quad \pi_1(X, x_0) \cong \pi_1(X, x_1).$$

Proof. To show that the *change-of-basepoint map* is isomorphism, we show that it's one-to-one and onto.

- one-to-one. Consider that if $[h \cdot \gamma \cdot \bar{h}] = [h \cdot \gamma' \cdot \bar{h}]$, then since we know that $h^{-1} = \bar{h}$, hence in the fundamental group $\pi_1(X, x_0)$, we see that

$$\bar{h} \cdot h \cdot \gamma \cdot \bar{h} \cdot h = \bar{h} \cdot h \cdot \gamma' \cdot \bar{h} \cdot h. \Rightarrow \gamma = \gamma'$$

as we desired.

- onto. We see that for every $\alpha \in \pi_1(X, x_0)$, there exists a $\gamma \in \pi_1(X, x_0)$ such that

$$\gamma = \bar{h} \cdot \alpha \cdot h \in \pi_1(X, x_1)$$

since $h \cdot \gamma \cdot \bar{h} = \alpha$.^a

We then see that the fundamental group of X does not depend on the choice of basepoint, only on the choice of the path component of the basepoint. If X is path-connected, it now makes sense to refer to the fundamental group of X and write $\pi_1(X)$ for the abstract group (up to isomorphism). ■

^aNotice that this is indeed the case, one can verify this by the fact that $h: x_0 \rightarrow x_1$ and $\bar{h}: x_1 \rightarrow x_0$.

Remark. We see that we can write $\pi_1(X)$ up to isomorphism if X is path-connected from Theorem 3.2.1.

Exercise. Composition of paths is well-defined on homotopy classes $\text{rel}\{0, 1\}$.

Exercise. If X is a contractible space, then X is path-connected and $\pi_1(X)$ is trivial.

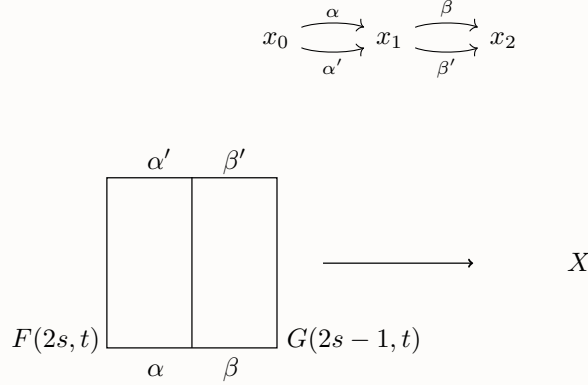
The followings are the properties about homotopy path. They are useful when we introduce fundamental groupoid.

Lemma 3.2.1. Given $x_0, x_1, x_2 \in X$, α, α' are two paths from x_0 to x_1 , and β, β' are two paths from x_1 to x_2 . If $\langle \alpha \rangle = \langle \alpha' \rangle$, $\langle \beta \rangle = \langle \beta' \rangle$, then $\langle \alpha \cdot \beta \rangle = \langle \alpha' \cdot \beta' \rangle$.

Proof. Given $\alpha \underset{F}{\simeq} \alpha' \text{ rel}\{0, 1\}$, $\beta \underset{G}{\simeq} \beta' \text{ rel}\{0, 1\}$, then we want to prove

$$\alpha \cdot \beta \simeq \alpha' \cdot \beta' \text{ rel}\{0, 1\}.$$

This is done by using [homotopy](#) $H: I \times I \rightarrow X$ such that it combines $F(2s, t)$ and $G(2s - 1, t)$.

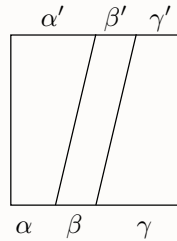


■

Lemma 3.2.2. Let $x_0, x_1, x_2, x_3 \in X$, α is a [path](#) from x_0 to x_1 , β is a [path](#) from x_1 to x_2 , γ is a [path](#) from x_2 to x_3 . Then

$$\langle (\alpha \cdot \beta) \cdot \gamma \rangle = \langle \alpha \cdot (\beta \cdot \gamma) \rangle.$$

Proof. We can write out the [homotopy](#) by the following diagram.

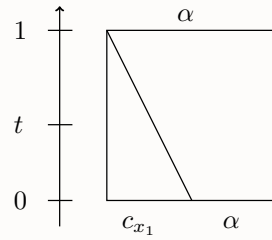


■

Lemma 3.2.3. Let X be a topological space, and $x_0 \in X$. Then for every [path homotopy](#) $\langle \alpha \rangle$ from x_1 to x_2 , we have

$$\langle c_{x_1} \cdot \alpha \rangle = \langle \alpha \rangle = \langle \alpha \cdot c_{x_2} \rangle.$$

Proof. We only need to prove $c_{x_1} \cdot \alpha \simeq \alpha \text{ rel}\{0, 1\}$. The [homotopy](#) can be written out explicitly by the following diagram.

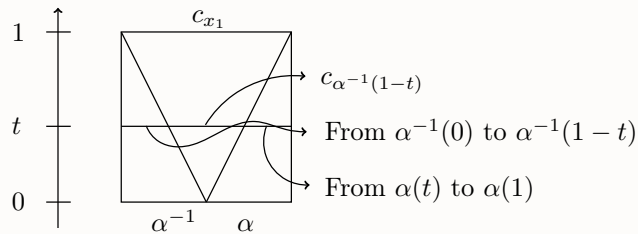


■

Lemma 3.2.4. For every path homotopy $\langle \alpha \rangle$ from x_1 to x_2 , then

$$\langle \alpha \cdot \alpha^{-1} \rangle = \langle c_{x_1} \rangle, \quad \langle \alpha^{-1} \cdot \alpha \rangle = \langle c_{x_2} \rangle.$$

Proof. For the first case, we have the following diagram.



The second case follows similarly.

■

3.2.2 Fundamental Groupoid

This section is not covered in class, but it's a useful concept. The idea is that after giving Definition 3.2.1, we see that we actually create a fundamental group at every point in X , furthermore, when we use Theorem 3.2.1 if X is path-connected, we actually lose some information about this space. Here is how we can store all the information.

Notation (Constant loop). We denote c_x , where $x \in X$ such that

$$c_x : [0, 1] \rightarrow X \\ t \mapsto x$$

as a constant loop.

Definition 3.2.2 (Groupoid). A category \mathcal{C} is a groupoid if any morphisms in \mathcal{C} is and isomorphism.

Remark. We'll soon see that for any topological space x , Definition 3.2.1 defines a groupoid, denoted by $\Pi(X)$.

Definition 3.2.3 (Fundamental groupoid). Let X denotes the space, then the category $\Pi(X)$ is a fundamental groupoid of X such that

- $\text{Ob}(\Pi(X)) := X$

- $\text{Hom}(\Pi(X)) : \forall p, q \in \text{Ob}(\Pi(X)) = X$,

$$\text{Hom}_{\Pi(X)}(p, q) := \{\text{Paths from } p \text{ to } q\} / \sim.$$

- Composition: For every $p, q, r \in \text{Ob}(\Pi(X)) = X$,

$$\begin{aligned} \circ : \text{Hom}_{\Pi(X)}(p, q) \times \text{Hom}_{\Pi(X)}(q, r) &\rightarrow \text{Hom}_{\Pi(X)}(p, r) \\ (\langle \alpha \rangle, \langle \beta \rangle) &\mapsto \langle \beta \rangle \circ \langle \alpha \rangle := \langle \alpha \cdot \beta \rangle. \end{aligned}$$

- Identity: For every $p \in \text{Ob}(\Pi(X)) = X$, we define $1_p := \langle c_p \rangle \in \text{Hom}_{\Pi(X)}(p, p)$ be the constant loop based at p such that for every $\langle \alpha \rangle \in \text{Hom}_{\Pi(X)}(p, q)$,

$$\langle \alpha \rangle \circ \text{id}_p = \text{id}_q \circ \langle \alpha \rangle = \langle \alpha \rangle.$$

- Associativity: Given $p, q, r, s \in \text{Ob}(\Pi(X)) = X$, with the paths

$$p \xrightarrow{\langle \alpha \rangle} q \xrightarrow{\langle \beta \rangle} r \xrightarrow{\langle \gamma \rangle} s$$

Then

$$\langle \gamma \rangle \circ (\langle \beta \rangle \circ \langle \alpha \rangle) = (\langle \gamma \rangle \circ \langle \beta \rangle) \circ \langle \alpha \rangle.$$

Proof. Note that in [Definition 3.2.3](#), we need to show some definitions are indeed well-defined, and we also need to show that $\Pi(X)$ is actually a [groupoid](#).

- Composition: Since if $\alpha \simeq \alpha', \beta \simeq \beta'$, we have

$$\alpha \cdot \beta \simeq \alpha' \cdot \beta'$$

from [Lemma 3.2.1](#).

- Identity: It follows that

$$\langle \alpha \rangle \circ \text{id}_p = \langle c_p \cdot \alpha \rangle = \langle \alpha \rangle$$

from [Lemma 3.2.3](#). The left identity can be shown similarly.

- Associativity: It's trivial in the sense that all the [homotopy](#) can be easily derived from [Lemma 3.2.2](#).

Additionally, from [Lemma 3.2.4](#), we see that given α is a [path](#) from p to q , then

$$\begin{cases} \langle \alpha^{-1} \cdot \alpha \rangle &= \langle c_q \rangle =: \text{id}_q \\ \langle \alpha \cdot \alpha^{-1} \rangle &= \langle c_p \rangle =: \text{id}_p. \end{cases}$$

Furthermore, since $\langle \alpha^{-1} \cdot \alpha \rangle = \langle \alpha \rangle \circ \langle \alpha^{-1} \rangle$ and $\langle \alpha \cdot \alpha^{-1} \rangle = \langle \alpha^{-1} \rangle \circ \langle \alpha \rangle$, hence this means $\Pi(X)$ is indeed a [groupoid](#). ■

Remark. Assume \mathcal{C} is a [groupoid](#), then for every $x \in \text{Ob}(\mathcal{C})$, we can define

$$\cdot : \text{Hom}_{\mathcal{C}}(x, x) \times \text{Hom}_{\mathcal{C}}(x, x) \rightarrow \text{Hom}_{\mathcal{C}}(x, x)$$

such that

$$(f, g) \mapsto f \cdot g := g \circ f.$$

We can prove that

$$(\text{Hom}_{\mathcal{C}}(x, x), \cdot)$$

defines a group $\text{Aut}_{\mathcal{C}}(x)$ called the *isotropy group* of \mathcal{C} at x .

Exercise. For every $x, y \in \text{Ob}(\mathcal{C})$, if there exists $f \in \text{Hom}_{\mathcal{C}}(x, y)$, then f induces

$$f_*: \text{Aut}_{\mathcal{C}}(x) \xrightarrow{\cong} \text{Aut}_{\mathcal{C}}(y),$$

where f_* is a group homomorphism.

Remark. For every $p \in X = \text{Ob}(\Pi(X))$, we have

$$\text{Aut}_{\Pi(X)}(p) = \pi_1(X, p).$$

Firstly, since they're the same in the sense of **set**:

$$\text{Aut}_{\Pi(X)}(p) = \text{Hom}_{\Pi(X)}(p, p) = \{\text{Loops in } X \text{ based at } p\} / \sim = \pi_1(X, p).$$

Hence, we only need to verify their group composition agrees. But this is trivial, since for every two $\langle \alpha \rangle, \langle \beta \rangle \in \text{Aut}_{\Pi(X)}(p)$,

$$\underbrace{\langle \alpha \rangle \cdot \langle \beta \rangle}_{\text{Composition from } \text{Aut}_{\Pi(X)}} = \langle \beta \rangle \circ \langle \alpha \rangle = \underbrace{\langle \alpha \cdot \beta \rangle}_{\text{Composition from } \pi_1}.$$

This implies that [Theorem 3.2.1](#) is just a particular example as a [groupoid](#).

Lecture 9: Calculate Fundamental Group

As previously seen. Intuitively, [fundamental group](#) is like a hole detector.

26 Jan. 10:00

3.3 Calculations of Fundamental Group of Spheres

Let's start with a basic but important theorem.

Theorem 3.3.1 (The fundamental group of S^1). The [fundamental group](#) of S^1 is

$$\pi_1(S^1) \cong \mathbb{Z},$$

and this identification is given by the [paths](#)

$$n \leftrightarrow [\omega_n(t) = (\cos(2\pi nt), \sin(2\pi nt))].$$

Proof. With the help of [covering spaces](#) and the theorems build around which, we can define

$$\begin{array}{ccc} p: \mathbb{R} \rightarrow S^1 & & \varphi: \mathbb{Z} \rightarrow \pi_1(S^1, 1) \\ x \mapsto e^{2\pi i x} & \text{and} & n \mapsto \langle p \circ \gamma_n \rangle \end{array}$$

where p defined above is a [covering map](#). We need to show that this is well-defined.

From the definition of φ , we see that it's a homomorphism. But we also need to show

- φ is a surjection. This is shown by [Corollary 4.1.1](#), specifically in the case of [path](#).
- φ is an injection. This is shown by [Corollary 4.1.1](#), specifically in the case of [homotopy of paths](#).

■

Remark. Intuitively, this winds around S^1 n times. The key to this proof was to understand S^1 via

the covering space $\mathbb{R} \rightarrow S^1$. We will talk about covering spaces much later.

Theorem 3.3.2. Given (X, x_0) and (Y, y_0) , then

$$\pi(X \times Y, (x_0, y_0)) \cong \pi_1(X, x_0) \times \pi_1(Y, y_0)$$

such that

$$\left[\begin{array}{l} r: I \rightarrow X \times Y \\ r(t) = (r_X(t), r_Y(t)) \end{array} \right] \mapsto (r_X, r_Y).$$

Proof. Let $Z \xrightarrow{f} X \times Y$ with $z \mapsto (f_X(z), f_Y(z))$. Then we have

$$f \text{ continuous} \Leftrightarrow f_X, f_Y \text{ are continuous.}$$

Now, apply above to

- Paths $I \rightarrow X \times Y$.
- Homotopies of paths $I \times I \rightarrow X \times Y$.

■

Corollary 3.3.1 (The fundamental group of S^k). The torus $T \cong S^1 \times S^1$ has fundamental group $\pi_1(T) \cong \mathbb{Z}^2$. Additionally, for a k -torus

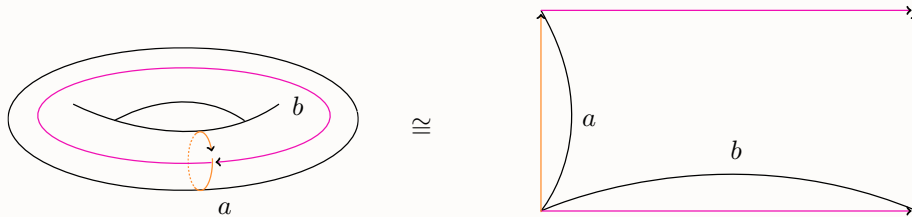
$$\underbrace{S^1 \times S^1 \times \dots \times S^1}_{k \text{ times}} = (S^1)^k,$$

the fundamental group is then \mathbb{Z}^k , i.e.

$$\pi_1((S^1)^k) \cong \mathbb{Z}^k.$$

Proof idea. Since

$$\pi_1 \cong \mathbb{Z}^2 \cong \mathbb{Z}_a \oplus \mathbb{Z}_b.$$



■

Remark. One way to think of the k -torus is as a k -dimensional cube with opposite $(k-1)$ -dimensional faces identified by translation.

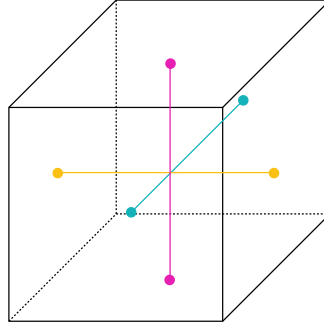


Figure 3.2: 3-torus with cube identified with parallel sides.

Lemma 3.3.1. Let $f, g: X \rightarrow Y$ such that $f \simeq_F g$. Let $x_0 \in X$, then given

$$f_*: \pi_1(X, x_0) \rightarrow \pi_1(Y, f(x_0))$$

$$g_*: \pi_1(X, x_0) \rightarrow \pi_1(Y, g(x_0))$$

with $\gamma: [0, 1] \rightarrow Y, t \mapsto F(x_0, t)$,

$$\gamma_*: \pi_1(Y, f(x_0)) \rightarrow \pi_1(Y, g(x_0))$$

$$\langle \alpha \rangle \mapsto \langle \gamma^{-1} \cdot \alpha \cdot \gamma \rangle,$$

the following diagram commutes.

$$\begin{array}{ccc}
 & \pi_1(Y, f(x_0)) & \\
 f_* \nearrow & \downarrow \gamma_* & \\
 \pi_1(X, x_0) & & \pi_1(Y, g(x_0)) \\
 g_* \searrow & &
 \end{array}$$

Proof. We want to prove that for any $\langle \alpha \rangle \in \pi_1(X, x_0)$, we have

$$\gamma_* \circ f_*(\langle \alpha \rangle) = g_*(\langle \alpha \rangle).$$

The left-hand side is just

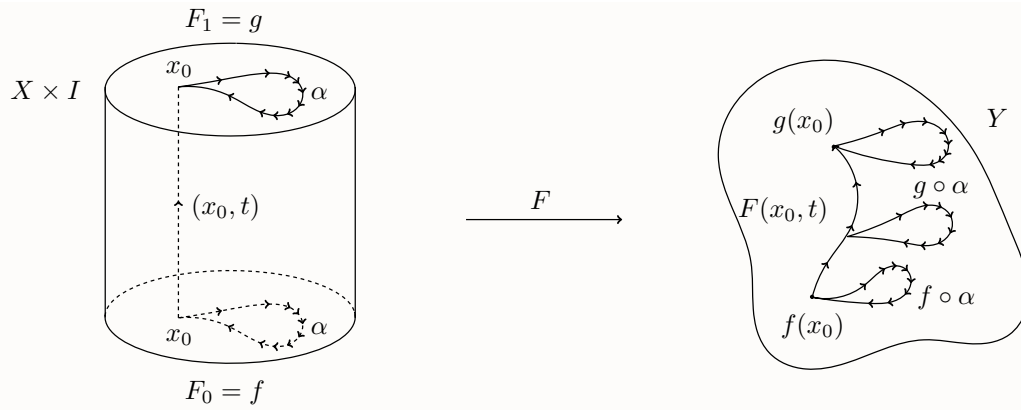
$$\gamma_* \circ f_*(\langle \alpha \rangle) = \gamma_*(\langle f \circ \alpha \rangle) = \langle \gamma^{-1} \cdot (f \circ \alpha) \cdot \gamma \rangle,$$

while the right-hand side is just

$$g_*(\langle \alpha \rangle) = \langle g \circ \alpha \rangle.$$

That is, we now want to show

$$\langle \gamma^{-1} \cdot (f \circ \alpha) \cdot \gamma \rangle = \langle g \circ \alpha \rangle.$$



We see that we can obtain a **homotopy** $G: I \times I \rightarrow Y$ such that

$$G := F \circ (\alpha \times \text{id}),$$

where we define $\alpha \times \text{id}$ by

$$\alpha \times \text{id}: I \times I \rightarrow X \times I, \quad (s, t) \mapsto (\alpha(s), t).$$

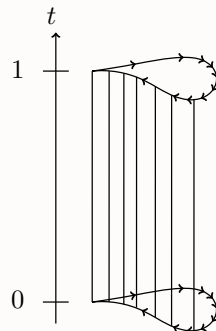
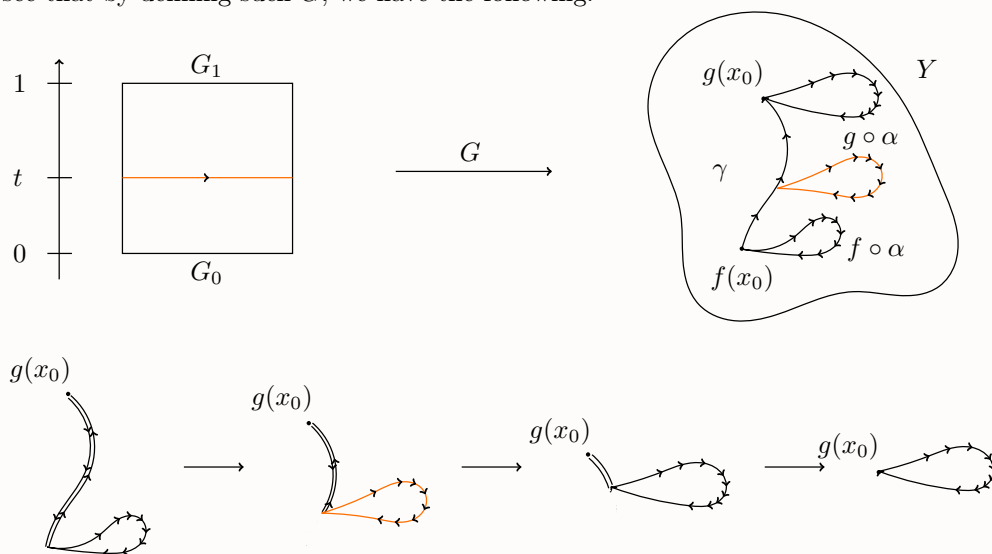
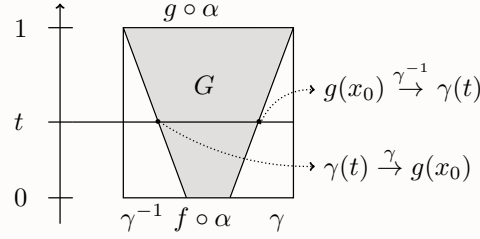


Figure 3.3: $\alpha \times \text{id}$'s image.

We see that by defining such G , we have the following.



To write out this **homotopy** explicitly, we see the following diagram.



Theorem 3.3.3 (Fundamental group is a homotopy invariant). If X, Y are homotopy equivalent, then their fundamental groups are isomorphic.

Proof.

HW.

Remark. This gives us a powerful tool to calculate π_1 .

Example. $\pi_1(S^\infty \times S^1) \cong \mathbb{Z}$.

Example. $\pi_1(\mathbb{R}^2 \setminus \{0\}) \cong 0 \times \mathbb{Z} = \mathbb{Z}$ since

$$\mathbb{R}^2 \setminus \{0\} \cong S^1 \times \mathbb{R},$$

which means that the generators are just loops around the hole intuitively.

3.4 Fundamental Group and Groupoid Define Functors

Theorem 3.4.1 (Fundamental group defines a functor). π_1 is a functor such that

$$\begin{aligned} \pi_1: \underline{\text{Top}}_* &\rightarrow \underline{\text{Gp}} \\ (X, x_0) &\mapsto \pi_1(X, x_0). \end{aligned}$$

While on a map $f: X \rightarrow Y$ taking base point x_0 to y_0 , π_1 induces a map

$$\begin{aligned} f_*: \pi_1(X, x_0) &\rightarrow \pi_1(Y, y_0) \\ [\gamma] &\mapsto [f \circ \gamma] \end{aligned}$$

i.e.,

$$[f: X \rightarrow Y] \mapsto [f_*: \pi_1(X, x_0) \rightarrow \pi_1(Y, f(x_0))].$$

Proof. We need to check

- well-defined on path homotopy classes.
- f_* is a group homomorphism.

$$f_*(\alpha \cdot \beta) = f_*(\alpha) \cdot f_*(\beta) = \begin{cases} f(\alpha(2s)), & \text{if } s \in \left[0, \frac{1}{2}\right] \\ f(\beta(1-2s)), & \text{if } s \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

- $(\text{id}_{(X, x_0)})_* = \text{id}_{\pi_1(X, x_0)}$

- $(f_* \circ g_*) = (f \circ g)_*$

$$(f \circ g)_*[\gamma] = [f \circ g \circ \gamma] = [f \circ (g \circ \gamma)] \Rightarrow f_*(\gamma_*(\gamma)).$$

DIY

$$\begin{array}{ccc} (X, x_0) & \rightsquigarrow & \pi_1(X, x_0) \\ f \downarrow & & \downarrow f_* \\ (Y, y_0) & \rightsquigarrow & \pi_1(Y, y_0) \end{array}$$

■

Remark. We usually write f_* if it's a **covariant functor**, while writing f^* if it's a **contravariant functor**.

Remark. We see that the construction of **fundamental group** is actually constructing a **functor**. Specifically,

$$\pi_1: \underline{\text{Top}}_* \rightarrow \underline{\text{Gp}}$$

such that

- on **objects**:

$$\forall (X, x_0) \in \text{Ob}(\underline{\text{Top}}_*), \quad \pi_1(X, x_0) = \text{fundamental group based at } x_0.$$

- on **morphisms**:

$$\forall f: (X, x_0) \rightarrow (Y, y_0), \quad \pi_1(f) = f_*: \pi_1(X, x_0) \rightarrow \pi_1(Y, y_0).$$

Our initial motivation is to construct a topological invariant, but we see that using π_1 , we need an additional **base point**. But as you already imagined, the **fundamental groupoid** actually is a **functor** as well.

Before we proceed further, we need to see the **category of groupoid**, denoted by $\underline{\text{Gpd}}$.

Definition 3.4.1 (Category of groupoid). The *category of groupoid*, denoted as $\underline{\text{Gpd}}$, contains the following data.

- $\text{Ob}(\underline{\text{Gpd}})$: **groupoids**.
- $\text{Hom}(\underline{\text{Gpd}})$: **functors** between **groupoids**.
- Composition: For every $\mathfrak{X}, \mathfrak{Y}, \mathfrak{Z} \in \text{Ob}(\underline{\text{Gpd}})$,

$$\mathfrak{X} \xrightarrow{F} \mathfrak{Y} \xrightarrow{G} \mathfrak{Z}$$

then $G \circ F: \mathfrak{X} \rightarrow \mathfrak{Z}$ is a **functor** defined as

- on **objects**: $\forall X \in \text{Ob}(\mathfrak{X}),$

$$G \circ F(X) := G(F(X)).$$
- on **morphisms**: $\forall X, Y \in \text{Ob}(\mathfrak{X})$ and $f: X \rightarrow Y,$

$$G \circ F(f) := G(F(f)).$$

- Identity. For every **groupoid** \mathfrak{X} , we define $\text{id}_{\mathfrak{X}}: \mathfrak{X} \rightarrow \mathfrak{X}$, where
 - $\forall X \in \text{Ob}(\mathfrak{X}), \text{id}_{\mathfrak{X}}(X) = X$
 - $\forall f \in \text{Hom}(\mathfrak{X}), \text{id}_{\mathfrak{X}}(f) = f.$

- Associativity. Since the composition is defined based on two **functors**,^a this holds trivially.

^aFor example, given $\mathfrak{X} \xrightarrow{F} \mathfrak{Y} \xrightarrow{G} \mathfrak{Z}$.

Proof. We need to show that the composition is well-defined. Specifically, we need to check

- $G \circ F(\text{id}_X) = \text{id}_{G \circ F(X)}$, since

$$G \circ F(\text{id}_X) = G(F(\text{id}_X)) = G(\text{id}_{F(X)}) = \text{id}_{G(F(X))} = \text{id}_{G \circ F(X)}.$$

- Given $X_1, X_2, X_3 \in \text{Ob}(\mathfrak{X})$ and

$$X_1 \xrightarrow{f} X_2 \xrightarrow{g} X_3$$

we want to show $G \circ F(g \circ f) = G \circ F(g) \circ G \circ F(f)$. Firstly, since G is a **functor**, hence

$$G \circ F(g) \circ G \circ F(f) = G(F(g)) \circ G(F(f)) = G(F(g) \circ F(f)).$$

Again, since F is a functor, so we further have

$$G \circ F(g) \circ G \circ F(f) = G(F(g \circ f)) = G \circ F(g \circ f).$$

■

Theorem 3.4.2 (Fundamental groupoid defines a functor). Π is a **functor** such that

$$\Pi: \underline{\text{Top}} \rightarrow \underline{\text{Gpd}},$$

where

- on **objects**: For every $X \in \text{Ob}(\underline{\text{Top}})$,

$$X \mapsto \Pi(X).$$

- on **morphisms**: for every $X, Y \in \text{Ob}(\underline{\text{Top}})$, $f: X \rightarrow Y$, define a **functor**

$$\Pi(f): \Pi(X) \rightarrow \Pi(Y)$$

such that

- on **objects**: For every $p \in \text{Ob}(\Pi(X)) = X$, $\Pi(f)(p) = f(p)$. i.e.,

$$\Pi(f): \underbrace{\text{Ob}(\Pi(X))}_X \rightarrow \underbrace{\text{Ob}(\Pi(Y))}_Y.$$

- on **morphisms**: For every $\langle \alpha \rangle \in \text{Hom}_{\Pi(X)}(p, q)$, define

$$\Pi(f)(\langle \alpha \rangle) := \langle f \circ \alpha \rangle \in \text{Hom}_{\Pi(Y)}(f(p), f(q)).$$

Proof. We need to check that the defined **functor** $\Pi(f)$ satisfies

- $\Pi(f)(\text{id}_p) = \text{id}_{f(p)}$. Indeed, since

$$\Pi(f)(\text{id}_p) = \Pi(f)(\langle c_p \rangle) = \langle f \circ d_p \rangle = \langle c_{f(p)} \rangle = \text{id}_{f(p)}.$$

- For every $p, q, r \in X = \text{Ob}(\Pi(X))$,

$$p \xrightarrow{\langle \alpha \rangle} q \xrightarrow{\langle \beta \rangle} r$$

we want to show $\Pi(f)(\langle\beta\rangle \circ \langle\alpha\rangle) = \Pi(f)(\langle\beta\rangle) \circ \Pi(f)(\langle\alpha\rangle)$. Indeed, since

$$\Pi(f)(\langle\beta\rangle \circ \langle\alpha\rangle) = \Pi(f)(\langle\alpha \cdot \beta\rangle) = \langle f \circ (\alpha \cdot \beta) \rangle,$$

and

$$\Pi(f)(\langle\beta\rangle) \circ \Pi(f)(\langle\alpha\rangle) = \langle f \circ \beta \rangle \circ \langle f \circ \alpha \rangle = \langle (f \circ \alpha) \cdot (f \circ \beta) \rangle.$$

Since $\langle f \circ (\alpha \cdot \beta) \rangle = \langle (f \circ \alpha) \cdot (f \circ \beta) \rangle$, hence $\Pi(f)$ is well-defined.

Now, we need to prove the same thing for Π , namely Π satisfies

- $\Pi(\text{id}_X) = \text{id}_{\Pi(X)}$ for all $X \in \text{Ob}(\underline{\text{Top}})$. This is trivial since

$$\Pi(\text{id}_X): \Pi(X) \rightarrow \Pi(X),$$

- on **objects**: $p \mapsto \text{id}_X(p) = p$.
- on **morphisms**: $p \xrightarrow{\langle\alpha\rangle} q \mapsto \langle \text{id}_X \circ \alpha \rangle = \langle\alpha\rangle$.

- For all $X, Y, Z \in \text{Ob}(\underline{\text{Top}})$,

$$X \xrightarrow{f} Y \xrightarrow{g} Z$$

then $\Pi(g \circ f) = \Pi(g) \circ \Pi(f)$. The diagrams are as follows.

$$\Pi(g \circ f): \Pi(X) \rightarrow \Pi(Z)$$

and

$$\Pi(X) \xrightarrow{\Pi(f)} \Pi(Y) \xrightarrow{\Pi(g)} \Pi(Z)$$

We see that this equality is in the sense of **functor**, hence we consider

- on **objects**: For every $p \in \text{Ob}(\Pi(X)) = X$, $\Pi(g \circ f)(p) = g \circ f(p)$ and

$$\Pi(g) \circ \Pi(f)(p) = \Pi(g)(\Pi(f)(p)) = \Pi(g)(f(p) = g(f(p))),$$

hence they're the same.

- on **morphisms**: For all $\langle\alpha\rangle \in \text{Hom}_{\Pi(X)}(p, q)$,
 - * $\Pi(g \circ f)(\langle\alpha\rangle) = \langle (g \circ f) \circ \alpha \rangle$.
 - * $\Pi(g) \circ \Pi(f)(\langle\alpha\rangle) = \Pi(g)(\underbrace{\Pi(f)(\langle\alpha\rangle)}_{\langle f \circ \alpha \rangle}) = \langle g \circ (f \circ \alpha) \rangle$.

We see that they're the same. ■

Lecture 10: Seifert-Van Kampen Theorem

The goal is to compute $\pi_1(X)$ where $X = A \cup B$ using the data

$$\pi_1(A), \pi_1(B), \pi_1(A \cap B).$$

26 Jan. 10:00

3.5 Free Product

We first introduce a definition.

Definition 3.5.1 (Free product). Given some collections of groups $\{G_\alpha\}_\alpha$, the *free product*, denoted by $\ast_\alpha G_\alpha$ is a group such that

- Elements: **Words** in $\{g: g \in G_\alpha \text{ for any } \alpha\}$ modulo by the equivalence relation generated by

$$wg_i g_j v \sim w(g_i g_j) v$$

when both $g_i, g_j \in G_\alpha$. Also, for the identity element $\text{id} = e_\alpha \in G_\alpha$ for any α such that

$$we_\alpha v \sim wv.$$

Specifically,

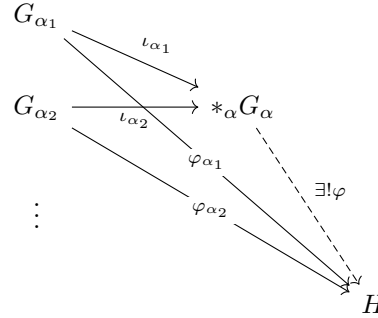
$$*_\alpha G_\alpha := \{\text{words in } \{G_\alpha\}_\alpha\} / \sim.$$

- Operation: Concatenation of **words**.

Remark. In particular, we have the following universal property of $*_\alpha G_\alpha$. For every α , there is a ι_α such that

$$\iota_\alpha: G_\alpha \rightarrow *_\alpha G_\alpha, \quad g \mapsto \bar{g},$$

where ι_α is a group homomorphism obviously. Further, $(*_\alpha G_\alpha, \iota_\alpha)$ satisfies the following property: For every group H and a group homomorphism $\varphi_\alpha: G_\alpha \rightarrow H$ for all α , there exists a unique group homomorphism $\varphi: *_\alpha G_\alpha \rightarrow H$ such that $\varphi \circ \iota_\alpha = \varphi_\alpha$, i.e., the following diagram commutes.



Proof. The proof is straightforward. Firstly, we define $w = \overline{g_1 g_2 \dots g_n} \in *_\alpha G_\alpha$, $g_i \in G_{\alpha_i}$,

$$\varphi(w) := \varphi_{\alpha_1}(g_1) \dots \varphi_{\alpha_n}(g_n).$$

Now, we just need to check

- It's well-defined, since φ_α is a group homomorphism.
- φ is a group homomorphism.
- $\varphi \circ \iota_\alpha = \varphi_\alpha$.
- Such φ is unique. Suppose there exists another $\psi: *_\alpha G_\alpha \rightarrow H$, then

$$\psi \circ \iota_\alpha = \varphi_\alpha \Rightarrow \forall_{g \in G_\alpha} \psi(\bar{g}) = \varphi_\alpha(g),$$

But then for every $w = \overline{g_1 g_2 \dots g_n} \in *_\alpha G_\alpha$, $g_i \in G_{\alpha_i}$, we have

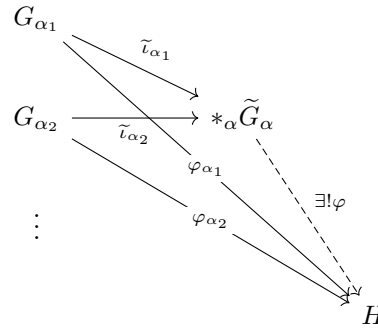
$$\psi(w) = \psi(\overline{g_1 \dots g_n}) = \psi(\bar{g_1}) \dots \psi(\bar{g_n}) = \varphi_{\alpha_1}(\overline{g_1}) \dots \varphi_{\alpha_n}(\overline{g_n}),$$

which is just φ .

⊛

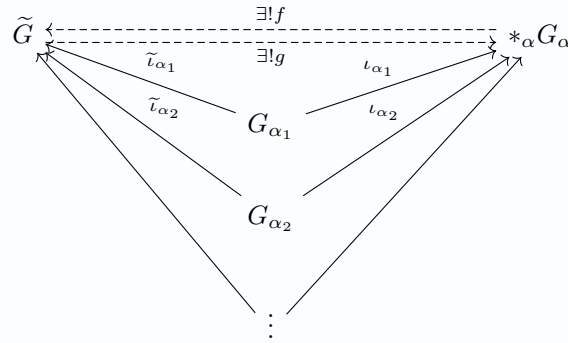
Remark. We further claim that this universal property determines such **free product** uniquely. i.e., assume there are another group \tilde{G} and $\tilde{\iota}_\alpha: G_\alpha \rightarrow \tilde{G}$. Assume $(\tilde{G}, \tilde{\iota}_\alpha)$ also satisfies the following

property: For every group H and group homomorphism $\varphi_\alpha: G_\alpha \rightarrow H$, then there exists a unique group homomorphism $\varphi: \tilde{G} \rightarrow H$ such that the following diagram commutes.



Then, $\tilde{G} \cong *_{\alpha} G_{\alpha}$.

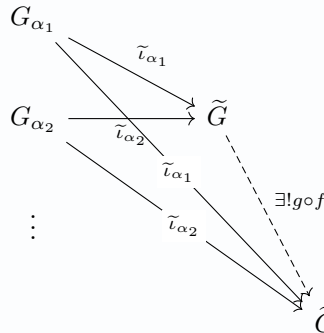
Proof. Assume $(\tilde{G}, \tilde{\iota}_{\alpha})$ satisfies the universal property mentioned above. Then from the universal property and viewing \tilde{G} and $*_{\alpha} G_{\alpha}$ as H separately, we obtain the following diagram.



We claim that

$$g \circ f = \text{id}, \quad f \circ g = \text{id}.$$

To see this, we simply apply the same observation, for example,



where $g \circ f$ comes from the previous diagram. But notice that id also makes the diagram commute, and since it's unique, hence $g \circ f = \text{id}$. Similarly, we have $f \circ g = \text{id}$. \circledast

If you're careful enough, you may find out that all we're doing is just writing out a specific example of [Lemma 2.2.1](#)! Indeed, this is exactly the construction of a [free group](#).

Definition 3.5.2 (Fibered coproduct). Given a [category](#) \mathcal{C} , let $f: Z \rightarrow X$, $g: Z \rightarrow Y$. The *fibered coproduct* between f and g is the data (W, p_1, p_2) , where $W \in \text{Ob}(\mathcal{C})$, $p_1: X \rightarrow W$, $p_2: Y \rightarrow W$ satisfy the following.

- The diagram commutes.

$$\begin{array}{ccc} Z & \xrightarrow{f} & X \\ g \downarrow & & \downarrow p_1 \\ Y & \xrightarrow{p_2} & W \end{array}$$

- For every $u: X \rightarrow U$, $v: Y \rightarrow U$ such that the following diagram commutes

$$\begin{array}{ccc} Z & \xrightarrow{f} & X \\ g \downarrow & & \downarrow p_1 \\ Y & \xrightarrow{p_2} & W \end{array} \quad \begin{array}{c} \searrow u \\ \exists! h \\ \swarrow v \end{array} \quad \begin{array}{c} \\ \\ U \end{array}$$

there exists a unique $h: W \rightarrow U$ such that $h \circ p_1 = u$, $h \circ p_2 = v$.

We say

$$\begin{array}{ccc} Z & \longrightarrow & X \\ \downarrow & & \downarrow \\ Y & \longrightarrow & W \end{array}$$

is a *Cocartesian* diagram.

Exercise. Prove that in a category \mathcal{C} , if the **fibred coproduct** of f and g exists

$$\begin{array}{ccc} Z & \xrightarrow{f} & X \\ g \downarrow & & \\ Y & & \end{array}$$

then such **fibred coproduct** is unique up to isomorphism.

Remark. If we reverse all the directions of **morphism**, then we have so-called *fibred product*.

Example. Let $\mathcal{C} = \underline{\text{Top}}$, and let $X \in \text{Ob}(\underline{\text{Top}})$. Given $X_0, X_1 \in X$, and $\text{Int}(X_0) \cup \text{Int}(X_1) = X$, if we have

$$\begin{aligned} i_0: X_0 &\hookrightarrow X, & i_1: X_1 &\hookrightarrow X \\ j_0: X_0 \cap X_1 &\hookrightarrow X_0, & j_1: X_0 \cap X_1 &\hookrightarrow X_1, \end{aligned}$$

then

$$\begin{array}{ccc} X_0 \cap X_1 & \xrightarrow{j_0} & X_0 \\ j_1 \downarrow & & \downarrow i_0 \\ X_1 & \xrightarrow{i_1} & X \end{array}$$

is a **cocartesian** diagram.

Proof. All we need to show is that given a topological space $Y \in \underline{\text{Top}}$ and $f: X_0 \rightarrow Y$, $g: X_1 \rightarrow Y$ in $\underline{\text{Top}}$, we have

$$f \circ j_0 = g \circ j_1.$$

$$\begin{array}{ccc}
 X_0 \cap X_1 & \xrightarrow{j_0} & X_0 \\
 j_1 \downarrow & & \downarrow i_0 \\
 X_1 & \xrightarrow{i_1} & X \\
 & \searrow g & \nearrow f \\
 & & Y
 \end{array}$$

$\exists! h$

We simply define $h: X \rightarrow Y$, $x \mapsto h(x)$ such that

$$h(x) = \begin{cases} f(x), & \text{if } x \in X_0; \\ g(x), & \text{if } x \in X_1. \end{cases}$$

h is clearly well-defined since the diagram commutes, so if $x \in X_0 \cap X_1$, then $f(x) = g(x)$. The only thing we need to show is that h is continuous. But this is obvious too since $X = \text{Int}(X_0) \cup \text{Int}(X_1)$, and

$$h|_{\text{Int}(X_0)} = f|_{\text{Int}(X_0)}, \quad h|_{\text{Int}(X_1)} = g|_{\text{Int}(X_1)}.$$

The uniqueness is trivial, hence this is indeed a **cocartesian** diagram. *

Example. Let $\mathcal{C} = \underline{\text{Top}}_*$. Given $p \in X_0 \cap X_1$, where all other data are the same with the above example, we see that

$$\begin{array}{ccc}
 (X_0 \cap X_1, p) & \xrightarrow{j_0} & (X_0, p) \\
 j_1 \downarrow & & \downarrow i_0 \\
 (X_1, p) & \xrightarrow{i_1} & (X, p)
 \end{array}$$

is a **cocartesian** diagram.

Example. Let $\mathcal{C} = \underline{\text{Gp}}$. Given $P, G, H \in \text{Ob}(\underline{\text{Gp}})$, we claim that the **fibred coproduct** of i and j exists.

$$\begin{array}{ccc}
 P & \xrightarrow{i} & G \\
 j \downarrow & & \\
 H & &
 \end{array}$$

Consider $G * H$ be the **free product** between G and H , with two inclusions

$$\iota_1: G \hookrightarrow G * H, \quad \iota_2: H \hookrightarrow G * H.$$

$$\begin{array}{ccc}
 P & \xrightarrow{i} & G \\
 j \downarrow & & \downarrow \iota_1 \\
 H & \xrightarrow{\iota_2} & G * H
 \end{array}$$

Let

$$N := \langle \{ \iota_1 \circ i(x) \cdot (\iota_2 \circ j(x))^{-1} \mid x \in P \} \rangle,$$

we define

$$G *_p H = G * H / N.$$

$$\begin{array}{ccc}
 P & \xrightarrow{i} & G \\
 j \downarrow & & \downarrow \iota_1 \\
 H & \xrightarrow{\iota_2} & G * H \\
 & \searrow \nu & \nearrow \pi \\
 & & G *_p H
 \end{array}$$

τ

We claim that

$$\begin{array}{ccc} P & \xrightarrow{i} & G \\ j \downarrow & & \downarrow \tau \\ H & \xrightarrow{\nu} & G *_p H \end{array}$$

is a [cocartesian](#) diagram in $\underline{\mathbf{Gp}}$.

Proof. Firstly, since it's just an outer diagram from above, hence it commutes. So we only need to prove this diagram satisfies the second diagram. Given any group K , for every $f: G \rightarrow K$, $g: H \rightarrow K$ such that the following diagram commutes.

$$\begin{array}{ccc} P & \xrightarrow{i} & G \\ j \downarrow & & \downarrow \tau \\ H & \xrightarrow{\nu} & G *_p H \end{array} \quad \begin{array}{c} \searrow f \\ \downarrow \tau \\ \searrow h \\ \downarrow g \\ \searrow g \end{array} \quad \begin{array}{c} \\ \\ \\ \\ K \end{array}$$

We want to prove that there exists a unique $h: G *_p H \rightarrow K$ such that this diagram still commutes. The idea is simple, from the universal property of $G * H$, we see that there exists a unique $\tilde{h}: G * H \rightarrow K$ such that

$$\tilde{h} \circ \iota_1 = f, \quad \tilde{h} \circ \iota_2 = g.$$

$$\begin{array}{ccccc} P & \xrightarrow{i} & G & & \\ j \downarrow & & \downarrow \tau & & \\ H & \xrightarrow{\nu} & G *_p H & & \\ & \nearrow \iota_2 & \nearrow \pi & \nearrow \tilde{h} & \\ & G * H & & & \end{array}$$

We see that we can actually factor \tilde{h} through π , as long as $\ker(\tilde{h}) \supset \ker(\pi)$. Now, since

$$\ker(\pi) = \langle \{ \iota_1 \circ i(x) \cdot (\iota_2 \circ j(x))^{-1} \mid x \in p \} \rangle,$$

we see that the kernel of π is indeed in the kernel of \tilde{h} since for every $x \in P$,

$$\tilde{h}(\iota_1 \circ i(x) \cdot (\iota_2 \circ j(x))^{-1}) = \underbrace{\tilde{h} \circ \iota_1}_{f} \circ i(x) \cdot \underbrace{\tilde{h} \circ \iota_2}_{g} \circ j(x^{-1}) = 1,$$

which implies $\ker(\tilde{h}) \supset \ker(\pi)$.

$$\begin{array}{ccc} G * H & \xrightarrow{\pi} & K \\ \tilde{h} \downarrow & & \\ G *_p H & & \end{array}$$

We then see that there exists a unique $h: G *_p H \rightarrow K$ such that the above diagram commutes. \circledast

3.5.1 Free Product with Amalgamation

After seeing the above examples, the following definition should make sense.

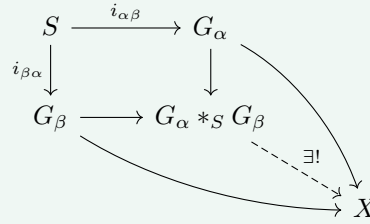
Definition 3.5.3 (Free product with amalgamation). If two groups G_α and G_β have a common subgroup $S_{\{\alpha,\beta\}}$ ^a, given two inclusion maps^b $i_{\alpha\beta}: S_{\{\alpha,\beta\}} \rightarrow G_\alpha$ and $i_{\beta\alpha}: S_{\{\alpha,\beta\}} \rightarrow G_\beta$, the *free product with amalgamation* ${}_{\alpha} *_S G_\alpha$ is defined as ${}_{\alpha} * G_\alpha$ modulo the **normal subgroup** generated by

$$\{i_{\alpha\beta}(s_{\{\alpha,\beta\}})i_{\beta\alpha}(s_{\{\alpha,\beta\}})^{-1} \mid s_{\{\alpha,\beta\}} \in S_{\{\alpha,\beta\}}\},$$

Namely,^c

$${}_{\alpha} *_S G_\alpha = {}_{\alpha} * G_\alpha / \langle i_{\alpha\beta}(s_{\{\alpha,\beta\}})i_{\beta\alpha}(s_{\{\alpha,\beta\}})^{-1} \rangle$$

and satisfies the universal property described by the following commutative diagram.



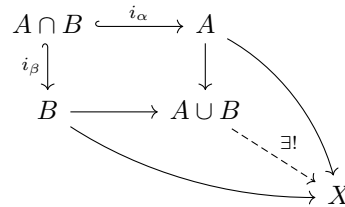
^aIn general, we don't need $S_{\{\alpha,\beta\}}$ to be a subgroup.

^bWe don't actually need $i_{\alpha\beta}, i_{\beta\alpha}$ to be inclusive as well.

^ci.e., $i_{\alpha\beta}(s)$ and $i_{\beta\alpha}(s)$ will be identified in the quotient.

Remark. We see that

- We can then write out **words** such as $g_\alpha \cdot s \cdot g_\beta$ for $s \in S$, and view s as an element of G_α or G_β . In fact, we can do this construction even when i_α and i_β are not injective, though this means we are not working with a subgroup.
- Aside, in Top, the same universal property defines union



for A, B are open subsets and the inclusion of intersection.

3.6 Seifert-Van Kampen Theorem

With [Definition 3.5.3](#), we can now see the important theorem.

Theorem 3.6.1 (Seifert-Van Kampen Theorem). Given (X, x_0) such that $X = \bigcup_{\alpha} A_{\alpha}$ with

- A_{α} are open and **path**-connected and $\forall \alpha \ x_0 \in A_{\alpha}$
- $A_{\alpha} \cap A_{\beta}$ is **path**-connected for all α, β .

Then there exists a surjective group homomorphism

$$*_{\alpha}: \pi_1(A_{\alpha}, x_0) \rightarrow \pi_1(X, x_0).$$

If we additionally have $A_\alpha \cap A_\beta \cap A_\gamma$ where they are all **path**-connected for every α, β, γ , then

$$\pi_1(X, x_0) \cong_{\alpha} \pi_1(A_\alpha \cap A_\beta, x_0) \pi_1(A_\alpha, x_0)$$

associated to all maps $\pi_a(A_\alpha \cap A_\beta) \rightarrow \pi_1(A_\alpha), \pi_1(A_\beta)$ induced by inclusions of spaces. i.e., $\pi_1(X, x_0)$ is a quotient of the **free product** $*_{\alpha} \pi_1(A_\alpha)$ where we have

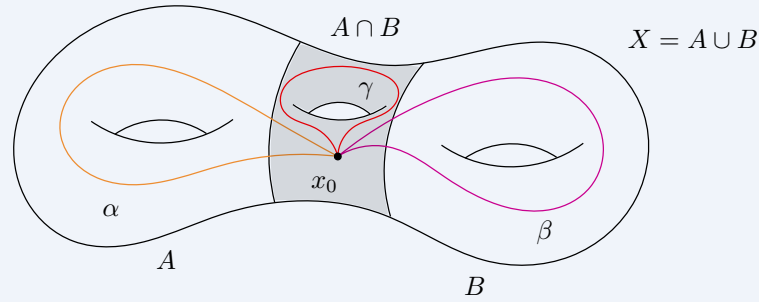
$$(i_{\alpha\beta})_*: \pi_1(A_\alpha \cap A_\beta) \rightarrow \pi_1(A_\alpha)$$

which is induced by the inclusion $i_{\alpha\beta}: A_\alpha \cap A_\beta \rightarrow A_\alpha$. We then take the quotient by the **normal subgroup** generated by

$$\{(i_{\alpha\beta})_*(\gamma)(i_{\beta\alpha})_* \mid \gamma \in \pi_1(A_\alpha \cap A_\beta)\}.$$

We'll defer the **proof** of [Theorem 3.6.1](#) until we get familiar with this theorem.

Example. We first see a great visualization of the [Theorem 3.6.1](#).



Intuitively we see the **fundamental group** of X , which is built by gluing A and B along their intersection. As the **fundamental group** of A and B glued along the **fundamental group** of their intersection. In essence, $\pi_1(X, x_0)$ is the quotient of $\pi_1(A) * \pi_1(B)$ by relations to impose the condition that loops like γ lying in $A \cap B$ can be viewed as elements of either $\pi_1(A)$ or $\pi_1(B)$.

Remark. We can use a more abstract way to describe [Theorem 3.6.1](#). Specifically, in the case that $n = 2$, i.e., $X = \bigcup_{i=1}^2 A_i$, we let $A_i =: X_i$, then we have the following. The **functor** $\pi_1: \underline{\text{Top}}_* \rightarrow \underline{\text{Gp}}$ maps the **cocartesian** diagram in $\underline{\text{Top}}_*$ to a **cocartesian** diagram in $\underline{\text{Gp}}$ as follows.

$$\begin{array}{ccccc} (X_0 \cap X_1, x_0) & \xrightarrow{j_0} & (X_0, x_0) & & \pi_1(X_0 \cap X_1, x_0) & \xrightarrow{(j_0)_*} & \pi_1(X_0, x_0) \\ j_1 \downarrow & & \downarrow i_0 & \xleftarrow{\pi_1} & (j_1)_* \downarrow & & \downarrow (i_0)_* \\ (X_1, x_0) & \xrightarrow{i_1} & (X, x_0) & & \pi_1(X_1, x_0) & \xrightarrow{(i_1)_*} & \pi_1(X, x_0) \end{array}$$

Then, simply from the property of **cocartesian** diagram, we see that

$$\pi_1(X, x_0) \cong \pi_1(X_0, x_0) *_{\pi_1(X_0 \cap X_1, x_0)} \pi_1(X_1, x_0).$$

Additionally, there is a more general version of [Theorem 3.6.1](#), which is defined on **groupoid**. The theorem is stated in [Appendix A.1](#) with the proof.

With this more general version and the proof of which, we can apply it to [Theorem 3.6.1](#). But one question is that, the above proof works in $\underline{\text{Gpd}}$ rather than in $\underline{\text{Gp}}$. We now see how to generalize a group to a **groupoid**.

For any group G , we can define a **groupoid**, denoted as G also, as follows.

- $\text{Ob}(G) = \{*\}$, a one point set.
- $\text{Hom}(G) = \{g \in G\}$.
- Composition: We define $g \circ h := h \cdot g$.

We see that the associativity of group elements implies the associativity of composition defined above, and since there is an identity element in G , hence we also have an identity [morphism](#), these two facts ensure that G is an [category](#).

Furthermore, since for every $g \in G$, there is a $g^{-1} \in G$, hence every [morphism](#) is an isomorphism, which implies G is a [groupoid](#).

With this, we see that we can view the following diagram in the [category](#) of [groupoid](#) $\underline{\text{Gpd}}$.

$$\begin{array}{ccc} \pi_1(X_0 \cap X_1, x_0) & \xrightarrow{(j_0)_*} & \pi_1(X_0, x_0) \\ (j_1)_* \downarrow & & \downarrow (i_0)_* \\ \pi_1(X_1, x_0) & \xrightarrow{(i_1)_*} & \pi_1(X, x_0) \end{array}$$

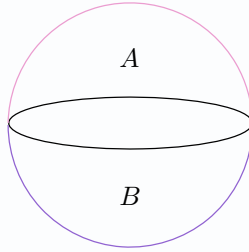
And to prove [Theorem 3.6.1](#), we only need to show this diagram is [cocartesian](#). This version of proof is given in [Appendix A.2](#).

Lecture 11: Group Presentations

Example (Fundamental group of S^2). We can use [Seifert Van Kampen Theorem](#) to compute the [fundamental group](#) of S^2 .

31 Jan. 10:00

Proof. We have the following [CW complex](#) structure on S^2 as follows.



We see that $\pi_1(S^2)$ must be a quotient of $\pi_1(A) * \pi_1(B)$, but since $A, B \simeq D^2$, we know that $\pi_1(A)$ and $\pi_1(B)$ are both zero groups, thus $\pi_1(A) * \pi_1(B)$ is the zero group, and $\pi_1(S^2)$ is also the zero group.

Remark. Note that the inclusion of $A \cap B \hookrightarrow A$ induces the zero map $\pi_1(A \cap B) \rightarrow \pi_1(A)$, which cannot be an injection. In fact, we know that $\pi_1(A \cap B) \cong \mathbb{Z}$ since $A \cap B \simeq S^1$.

⊗

Example (Fundamental group of T). We can use [Seifert Van Kampen Theorem](#) to compute the [fundamental group](#) of a torus T .

Proof. In the case of torus, consider the following [CW complex](#) structure.

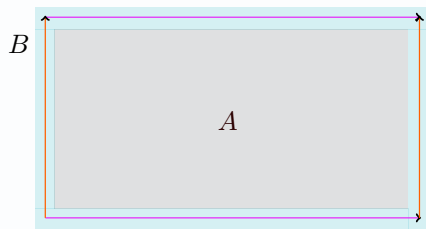


Figure 3.4: A is the interior, while B is the neighborhood of the boundary.

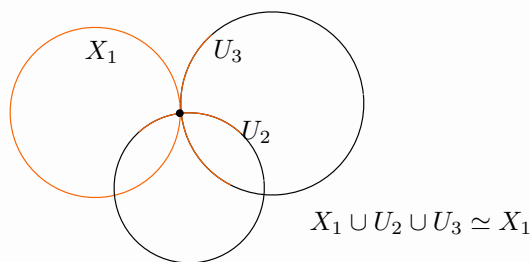
Now note that $A \simeq D^2$ and $B \simeq S^1 \vee S^1$, and since it's a thickening of the two loops around the torus in both ways, this suggests the question of how do we find $\pi_1(B)$? We grab a bit of knowledge from [Seifert Van Kampen Theorem](#) before we continue.

Exercise. Suppose we have [path-connected](#) spaces (X_α, x_α) , and we take their [wedge sum](#) $\bigvee_\alpha X_\alpha$ by identifying the points x_α to a single point x . We also suppose a mild condition for all α , the point x_α is a [deformation retract](#) of some neighborhood of x_α .

For example, this doesn't work if we choose the *bad point* on the Hawaiian earring. Then we can use [Seifert Van Kampen Theorem](#) to show that

$$\pi_1\left(\bigvee_\alpha X_\alpha, x\right) \cong *_\alpha \pi_1(X_\alpha, x_\alpha).$$

Answer. If we denote the [wedge](#) of circles as C_n ,^a then $\pi_1(C_n) \cong F_n$.



We can then apply [Theorem 3.6.1](#) to $A_\alpha = X_\alpha \cup_\beta U_\beta$. Specifically, take $A_\alpha = X_\alpha \cup_\beta U_\beta \simeq X_\alpha$, where U_β is a neighborhood of x_β which [deformation retracts](#) to x_β . This makes A_α open as desired. ⊗

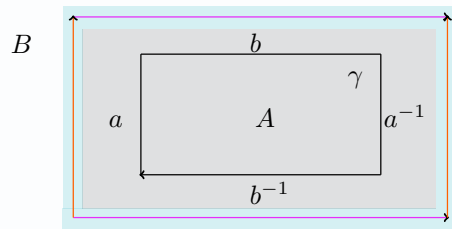
^aIn this case, $n = 3$.

Corollary 3.6.1. The [wedge sum](#) of circles $\pi_1(\bigvee_{\alpha \in A} S^1) = *_\alpha \mathbb{Z}$ is a [free group](#) on A . In particular, when A is finite, the [fundamental group](#) of a bouquet of circles is the [free group](#) on $|A|$.

Returning to the current example, we see that

- $\pi_1(A) = 0$
- $\pi_1(B) = \pi_1(S^1 \vee S^1) = \mathbb{Z} * \mathbb{Z} = F_2$
- $\pi_1(A \cap B) = \pi_1(S^1) = \mathbb{Z}$

Further, we know that $\pi_1(A \cap B) \rightarrow \pi_1(A)$ is the zero map. We need to understand $\pi_1(A \cap B) \rightarrow \pi_1(B)$. To do so we need to understand how we're able to identify $\pi_1(S^1 \vee S^1)$ with F_2 and how we identify $\pi_1(S^1)$ with \mathbb{Z} . We update our [Figure 3.4](#) to talk about this.



From this, we have

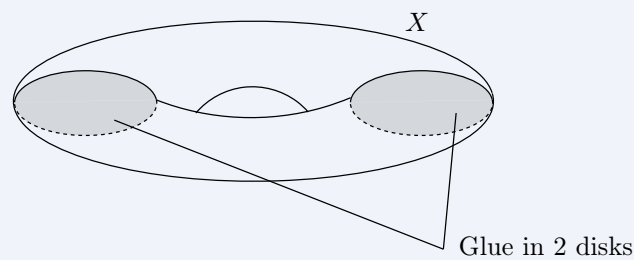
$$\begin{aligned}\pi_1(A \cap B) &\rightarrow \pi_1(B) \cong F_{a,b} \\ \gamma &\mapsto aba^{-1}b^{-1}.\end{aligned}$$

By [Seifert Van Kampen Theorem](#), we identify the image of γ in $\pi_1(B)$ as $[aba^{-1}b^{-1}]$ with its image in $\pi_1(A)$, which is just trivial. Therefore, we have

$$\pi_1(T^2) = F_{a,b} / \langle aba^{-1}b^{-1} \rangle \cong \mathbb{Z}^2.$$

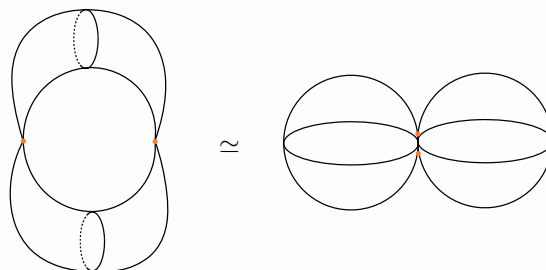
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Example. Let's see the last example which illustrate the power of [Seifert Van Kampen Theorem](#). Start with a torus, and we glue in two disks into the hollow inside.

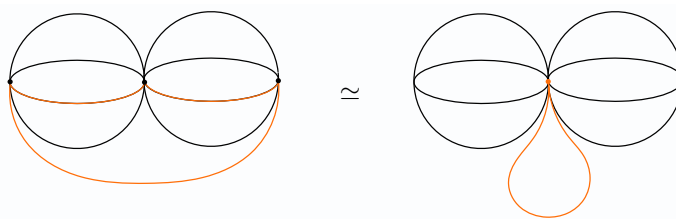


We'll call this space X , and our goal is to find $\pi_1(X)$.

Proof. We can place a [CW complex](#) structure on this space so that each disk is a [subcomplex](#). Then, we take [quotient](#) of each disk to a point without changing the [homotopy type](#), hence X is [homotopy](#) to



By the same property, we can expand one of those points into an interval, and then contract the red [path](#) as follows.



This is exactly $S^2 \vee S^2 \vee S^1$. With [Seifert Van Kampen Theorem](#), we have

$$\pi_1(X) = \pi_1(S^2 \vee S^2 \vee S^1) = 0 * 0 * \mathbb{Z} \cong \mathbb{Z}.$$

⊛

Exercise. Consider $\mathbb{R}^2 \setminus \{x_1, \dots, x_n\}$, that is the plane punctured at n points. Show that

$$\pi_1(X) \simeq F_n.$$

Answer. Observe that $X \simeq \bigvee_n S^1$, so one way to do this is to convince yourself that you can do a [deformation retract](#) the plane onto the following [wedge](#).

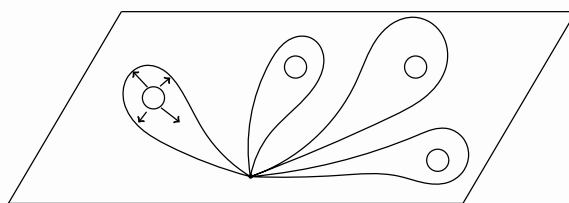


Figure 3.5: [Deformation retract](#) X onto [wedge](#).

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3.7 Group Presentation

In order to go further, we introduce the concept of *group presentation*.

Definition 3.7.1 (Group presentation). A *presentation* $\langle S \mid R \rangle$ of a group G such that

$$G \cong F_S / \langle R \rangle,$$

where $\langle R \rangle$ is a [subgroup normally](#) generated by the elements of R . We further call

Definition 3.7.2 (Generator). S is the set of *generators*.

Definition 3.7.3 (Relater). R is the set of *relaters* ([words](#) in a [generator](#) and inverses).

Definition 3.7.4 (Finite presentation). If S and R are both finite, then $G = \langle S \mid R \rangle$ is a *finite presentation* if S, R are, and we say that G is *finitely presented*.

Note. One way to think about whether G is **finitely presented** is that if r is a **word** in R then $r = 1$, where 1 is the identity of G .

Example. We see that

- (1) $F_2 = \langle a, b \mid \rangle$
- (2) $\mathbb{Z}^2 = \langle a, b \mid aba^{-1}b^{-1} \rangle = \langle a, b \rangle / \overline{\{aba^{-1}b^{-1}\}}$
- (3) $\mathbb{Z}/3\mathbb{Z} = \langle a \mid a^3 \rangle$
- (4) $S_3 = \langle a, b \mid a^2, b^2, (ab)^3 \rangle$

Theorem 3.7.1. Any group G has a **presentation**.

Proof. We first choose a generating set S for G . Notice that we can even choose $S = G$ directly. From the universal property of **free group**, we see that there exists a surjective map $\varphi: F_S \rightarrow G, s \mapsto s$. Now, let R be the generating set for $\ker(\varphi)$, by the first isomorphism theorem^a, $G \cong F_S / \ker \varphi$. In fact, we have $G = \langle S \mid R \rangle$.

Specifically, $i: S \rightarrow G$ with $\iota: S \rightarrow F_S$, we have $\varphi \circ \iota = i$.

$$\begin{array}{ccc} S & \xrightarrow{\iota} & F_S \\ & \searrow i & \downarrow \exists! \varphi \\ & & G \end{array}$$

■

^ahttps://en.wikipedia.org/wiki/Isomorphism_theorems

Remark. The advantages of using **group presentation** are that given $G = \langle S \mid R \rangle$, it's now easy to define a homomorphism $\psi: G \rightarrow H$ given a map $\varphi: S \rightarrow H$, ψ extends to a group homomorphism $G \rightarrow H$ if and only if ψ vanishes on R , i.e., $\psi(r) = 1$ for all $r \in R$. We see an example to illustrate this.

Example. If we have $G = \langle a, b \mid aba \rangle$, a map $\varphi: \{a, b\} \rightarrow H$ gives a group homomorphism if and only if

$$\varphi(aba) = \varphi(a)\varphi(b)\varphi(a) = 1_H.$$

This essentially uses the universal property of quotients.

Remark. It's sometimes easy to calculate G^{Ab}

$$G^{\text{Ab}} = \langle S \mid R, \text{commutators in } S \rangle.$$

Example. Suppose all relations in R are commutators, so $R \subseteq [G, G]$. Then,

$$G^{\text{Ab}} = (F_S)^{\text{Ab}} = \bigoplus_S \mathbb{Z}.$$

Remark. The disadvantages are that this is computationally **very difficult**. Let's see an example to illustrate this.

Example. Given $\mathbb{Z}^2 = \langle a, b \mid aba^{-1}b^{-1} \rangle$, let

$$\psi: \{a, b\} \rightarrow H$$

extends to a homomorphism if and only if

$$\psi(a)\psi(b)\psi(a)^{-1}\psi(b)^{-1} = 1_H \in H.$$

Namely, this is a **presentation** of the trivial group, but this is entirely unclear.

Lecture 12: Presentations for Fundamental Group of CW Complexes

Let's first see an exercise.

2 Feb. 10:00

Exercise. Consider $G_1 = \langle S_1 \mid R_1 \rangle$ and $G_2 = \langle S_2 \mid R_2 \rangle$. Then

- $G_1 * G_2 = \langle S_1 \cup S_2 \mid R_1 \cup R_2 \rangle$
- $G_1 \oplus G_2 = \langle S_1 \cup S_2 \mid R_1 \cup R_2 \cup \{[g_1, g_2] \mid g_1 \in G_1, g_2 \in G_2\} \rangle$
- $G_1 *_H G_2$ where $f_1: H \rightarrow G_1$ and $f_2: H \rightarrow G_2$. Then we have

$$G_1 *_H G_2 = \langle S_1 \cup S_2 \mid R_1 \cup R_2 \cup \{f_1(h)f_2(h)^{-1} \mid h \in H\} \rangle.$$

3.7.1 Presentations for Fundamental Group of CW Complexes

For X a **CW complex**, we have

- (1) A 1-dimensional **CW complex** has **free** π_1 (call its generators as a_1, \dots, a_n).
- (2) Gluing a 2-disk by its boundary along a **word** w in the generators *kills* w in π_1 . We then get a **presentation** for $\pi_1(X^2)$ given by

$$\langle a_1, \dots, a_n \mid w \text{ for each 2-cell in } X_2 \rangle.$$

- (3) Gluing in any higher dimensional **cells** along their boundary will not change π_1 . That is, in a **CW complex**, we have $\pi_1(X) = \pi_1(X^2)$.

Remark. We can write the above more precise.

- (1) Find **free** generators $\{a_i\}_{i \in I}$ for $\pi_1(X^1)$.
- (2) For each 2-disk D_α^2 , write **attaching map** as **word** w_α in a_i . i.e., $\pi_1(X^2) = \langle a_i \mid w_\alpha \rangle$.
- (3) $\pi_1(X) = \pi_1(X^2)$.

Remark. Every group is π_1 of some space. Specifically, given a group G , we work with its **presentation** $\langle S \mid R \rangle$.

Proof. We first see a simple example to grab some intuition.

Example (Fundamental group as $\mathbb{Z}/n\mathbb{Z}$). Given $G = \mathbb{Z}/n\mathbb{Z} = \langle a \mid a^n \rangle$, find a space with its **fundamental group** being G .

Proof. We see that we can simply take a loop and then wind a 2-disk around the loop a for n times.

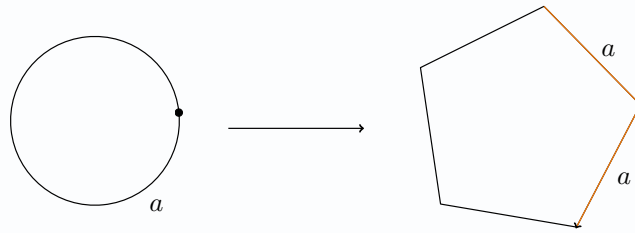


Figure 3.6: For $G = \mathbb{Z} / n\mathbb{Z} = \langle a \mid a^n \rangle$, we wind the boundary around a for n times.

⊗

We then see that given a group G with **presentation** $\langle S \mid R \rangle$, one can construct a 2-dimensional **CW complex** with $\pi_1 = G$ by

- Set $X^1 = \bigvee_{s \in S} S^1$
- For each relation $r \in R$, glue in a 2-disk along loops specified by the **word** r .

⊗

Theorem 3.7.2. If X is a **CW complex** and $\iota_1: X^1 \hookrightarrow X$ and $\iota_2: X^2 \hookrightarrow X$, then $(\iota_1)_*$ surjects onto π_1 and $(\iota_2)_*$ is an isomorphism on π_1 .

Proof. _____

■

HW

Lecture 13: Graph Structure of CW Complex

We can now put some kind of **graph** structure on a space X and relate it to the calculation of π_1 .

4 Feb. 10:00

Definition. We import some topological definitions of graph theoretic concepts.

Definition 3.7.5 (Graph). A *graph* is a 1-dimensional **CW complex**.

Definition 3.7.6 (Subgraph). A *subgraph* is a **subcomplex**.

Definition 3.7.7 (Tree). A *tree* is a contractible **graph**.

Definition 3.7.8 (Maximal tree). A **tree** in a **graph** X (necessarily a **subgraph**) is *maximal* or *spanning* if it contains all the vertices.

Theorem 3.7.3. Every connected **graph** has a **maximal tree**. Every **tree** is contained in a **maximal tree**.

Proof. _____

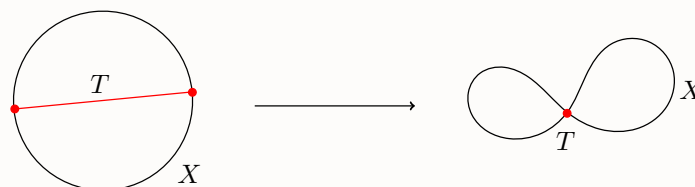
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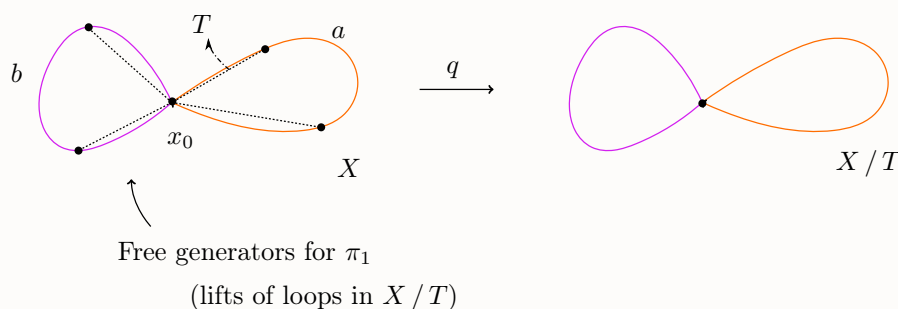
Corollary 3.7.1. Suppose X is a connected graph with basepoint x_0 . Then $\pi_1(X, x_0)$ is a free group.

Furthermore, we can give a presentation for $\pi_1(X, x_0)$ by finding a spanning tree T in X . The generators of π_1 will be indexed by cells $e_\alpha \in X - T$, and e_α will correspond to a loop that passes through T , traverses e_α once, then returns to the basepoint x_0 through T .

Proof. The idea is simple. X is homotopy equivalent to X/T via previous work on the homework, T contains all the vertices, so the quotient has a single vertex. Thus, it is a wedge of circles, and each e_α projects to a loop in X/T .



To be formal, we calculate the fundamental group of X by considering its CW complex structures. For now, we need to see that the fundamental group of a 1-skeleton (a graph) can be found by taking a maximal tree, and then quotienting out the space by the tree to get a wedge of circles.



We now prove that the maximal trees exist. Recall that X is a quotient of $X^0 \coprod_\alpha I_\alpha$. Since each subset U is open if and only if it intersects each edge \bar{e}_α in an open subset. A map $X \rightarrow Y$ if and only if its restriction to each edge \bar{e}_α is continuous. Now, take X_0 to be a subgraph. Our goal is to construct a subgraph Y with

- $X_0 \subset Y \subset X$
- Y deformation retracts to X_0
- Y contains all vertices of X .

So if we take X_0 to be a vertex, then Y is our tree, and the result follows.

So, we now build a sequence $X_0 \subset X_1 \subset \dots$ and correspondingly, $Y_0 \subset Y_1 \subset \dots$. We start with X_0 and inductively define

$$X_i := X_{i-1} \cup \text{all edges } \bar{e}_\alpha \text{ with one or both vertices in } X_{i-1}.$$

We then see that $X = \bigcup_i X_i$.^a Now, let $Y_0 = X_0$. By induction, we'll assume that Y_i is a subgraph of X_i such that

- Y_i contains all vertices of X_i .
- Y_i deformation retracts to Y_{i-1} .

Check.

We can then construct Y_{i+1} by taking Y_i and adding to it one edge to adjoin every vertex of X_{i+1} , namely

$$Y_{i+1} := Y_i \bigcup \text{one edge to adjoin every vertex of } X_i,$$

which is possible if we assume Axiom of Choice.

We then see that Y_{i+1} deformation retracts to Y_i by just smashing down each edge. Now, we can show that Y deformation retracts to $Y_0 = X_0$ by performing the deformation retraction from Y_i to Y_{i-1} during the time interval $[1/2^i, 1/2^{i-1}]$. ■

^aHatcher[HPM02] do this by arguing the union on the right is both open and closed.

Example (Fundamental group of S^n). Let

- S^n : decompose into 2 open disks
- A_1 : neighborhood of top hemisphere
- A_2 : neighborhood of lower hemisphere

We can then apply Theorem 3.6.1 and conclude that $\pi_1(S^n) = 0$.

Proof. We see that $A_1 \cap A_2 \simeq S^{n-1}$, where we need $n \geq 2$ to let S^{n-1} be connected. We then have

$$\pi_1(S^n) \cong 0 \underset{\pi_1(A_1 \cap A_2)}{*} 0 = 0.$$

On the other hand, if $n \geq 3$, then we see that

$$S^n = D^n \cup * \Big/ \sim.$$

Since 2-skeleton is a point, thus $\pi_1(S^n) = 0$. *

Chapter 4

Covering Spaces

Lecture 14: Covering Spaces Theory

4.1 Lifting Properties

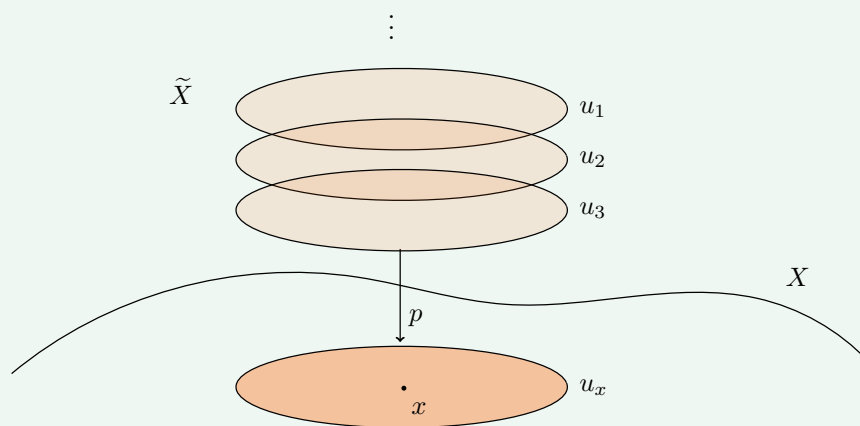
7 Feb. 10:00

As always, we start with a definition.

Definition 4.1.1 (Covering space). A *covering space* \tilde{X} of X is a space \tilde{X} and a map $p: \tilde{X} \rightarrow X$ such that $\forall x \in X \exists$ neighborhood u_x with $p^{-1}(u_x)$ the disjoint union of open sets $\coprod_{\alpha} u_{\alpha}$ such that

$$p|_{u_{\alpha}} : u_{\alpha} \rightarrow u_x$$

is a homeomorphism for every α .



Definition 4.1.2 (Covering map). We sometimes call p as the *covering map*.

Although we already investigate into [covering spaces](#) quite a lot in homework, but some terminologies are still worth mentioning.

Definition 4.1.3 (Evenly covered). Let $p: \tilde{X} \rightarrow X$ be a continuous map of spaces. Then an open subset $U \subseteq X$ is called *evenly covered by p* if

$$p|_{V_i} : V_i \rightarrow U$$

is a homeomorphism.

Lack of
content...
Things are
in Hw.

Definition 4.1.4 (Slice). Given a covering space \tilde{X} and the relating map p , we call the parts V_i of the partition $\coprod_i V_i$ of $p^{-1}(U)$ *slices*.

Remark. We see that p is a covering map if and only if every point $x \in X$ has a neighborhood which is evenly covered.

We immediately have the following proposition.

Proposition 4.1.1 (Homotopy lifting property). The covering spaces satisfy the homotopy lifting property such that the following diagram commutes.

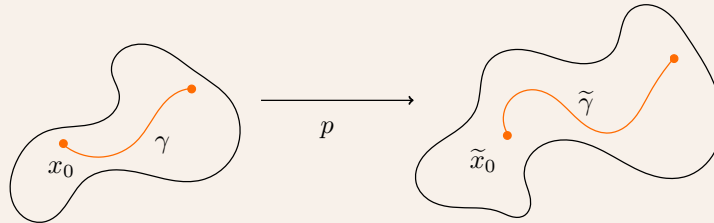
$$\begin{array}{ccc}
 X \times \{0\} & \xrightarrow{\tilde{F}_0} & \tilde{Y} \\
 \downarrow & \nearrow \exists! \tilde{F}_t & \downarrow p \\
 X \times I & \xrightarrow{F_t} & Y
 \end{array}$$

Proof. We already proved this in homework! ■

Definition 4.1.5 (Lift). We call \tilde{F}_t the *lift* of F_t in Proposition 4.1.1.

Corollary 4.1.1 (Path lifting property). For each path $\gamma: I \rightarrow X$ in X , $\tilde{x}_0 \in p^{-1}(\gamma(0))$ such that there exists a unique lift $\tilde{\gamma}$ starting at \tilde{x}_0 .

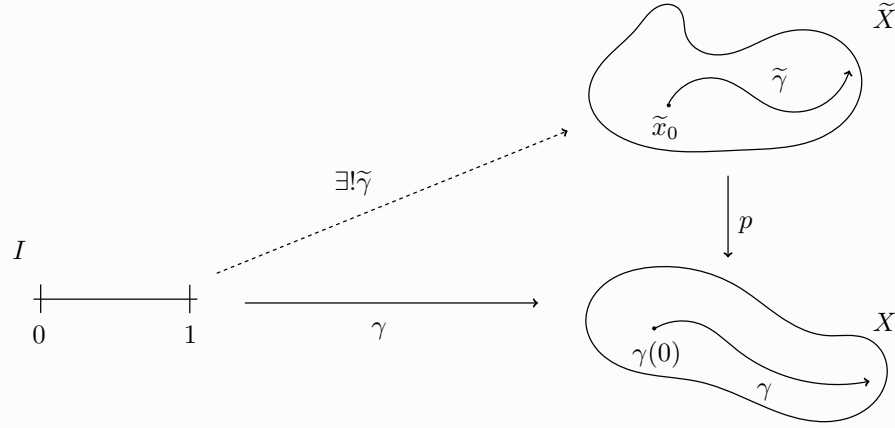
And for each path homotopy $I \times I \rightarrow X$, there exists a unique path homotopy $\tilde{\gamma}: I \times I \rightarrow \tilde{X}$ starting at \tilde{x}_0 .



Proof. We prove them separately.

Note. Though we can directly use Proposition 4.1.1 to prove this, but we can see some insight by directly proving this.

Lifting a path. Assume that we have the following lift.



We first prove that a [path](#) will be [lifted](#) uniquely to a [path](#) $\tilde{\gamma}$ from \tilde{x}_0 . For every $x \in X$, there exists an open neighborhood U_x such that

$$p^{-1}(U_x) = \coprod_{\alpha} U_{x_{\alpha}},$$

where for every α ,

$$p|_{U_{x_{\alpha}}} : U_{x_{\alpha}} \rightarrow U_x$$

is a homeomorphism. We see that $\{U_x \mid x \in X\}$ is an open cover of X , hence

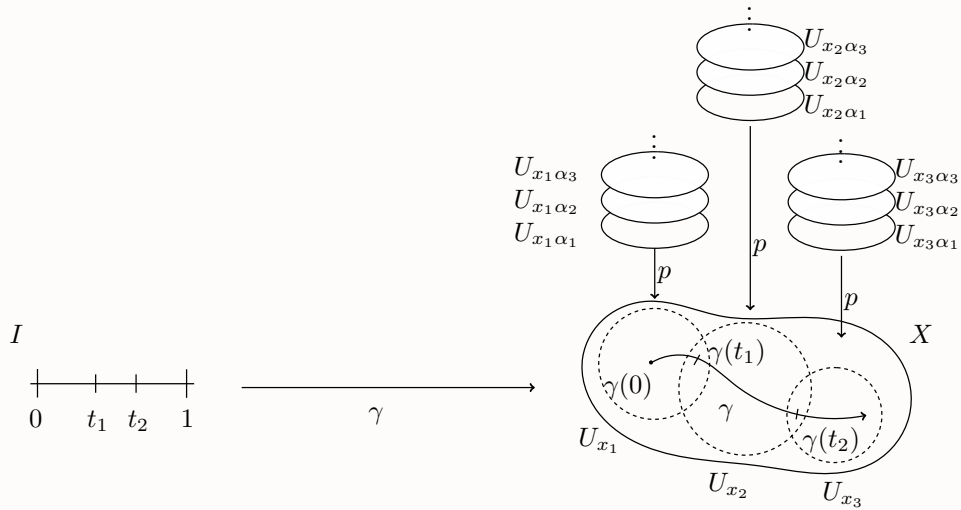
$$\{\gamma^{-1}(U_x) \mid x \in X\}$$

is an open cover of $[0, 1]$. Note that since $[0, 1]$ is a compact metric space, from Lebesgue Lemma^a, there exists a partition of $[0, 1]$ such that

$$0 = t_0 < t_1 < \dots < t_k = 1$$

such that for every i , $[t_i, t_{i+1}] \subset \gamma^{-1}(U_x)$ for some x . Without loss of generality, we assume that $[t_i, t_{i+1}] \subset \gamma^{-1}(U_{x_i})$, i.e.,

$$\gamma([t_i, t_{i+1}]) \subset U_{x_i}.$$



Now, since $p(\tilde{x}_0) = \gamma(0)$ for $\gamma_0 \in U_{x_1}$ and $\tilde{x}_0 \in p^{-1}(U_{x_1})$, we may assume $\tilde{x}_0 \in U_{x_1 \alpha_1}$. Consider [lifting](#) the first segment, namely $\gamma([0, t_1])$.



Specifically, let $\tilde{\gamma}_1(t) = \left(p|_{U_{x_1\alpha_1}}\right)^{-1} \circ \gamma(t)$ for $0 \leq t \leq t_1$, we see that

$$\tilde{\gamma}_1: [0, t_1] \rightarrow \tilde{X}$$

is a **lift** of $\gamma|_{[0,t_1]}$ from \tilde{x}_0 . We claim that this **lift** is unique. Consider there exists another **lift** from \tilde{x}_0 $\tilde{\tilde{\gamma}}_1: [0, t_1] \rightarrow \tilde{X}$, then since

- $\tilde{\tilde{\gamma}}_1(0) = \tilde{x}_0$
- $\tilde{\tilde{\gamma}}_1$ is continuous
- $\tilde{x}_0 \in U_{x_1\alpha_1}$,

we see that $\tilde{\tilde{\gamma}}_1([0, t_1]) \subset U_{x_1\alpha_1}$, which implies

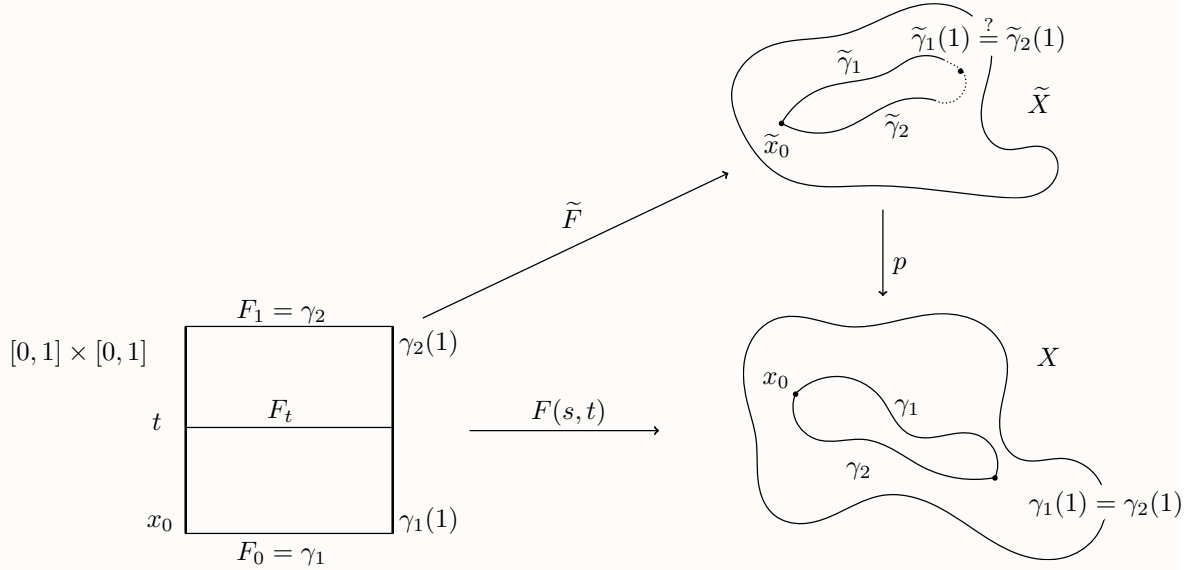
$$\begin{array}{ccc} [0, t_1] & \xrightarrow{\tilde{\tilde{\gamma}}_1} & U_{x_1\alpha_1} \\ & \searrow \gamma|_{[0,t_1]} & \downarrow p|_{U_{x_1\alpha_1}} \\ & & U_{x_1} \end{array} \Rightarrow \tilde{\tilde{\gamma}}_1 = \left(p|_{U_{x_1\alpha_1}}\right)^{-1} \circ \gamma|_{[0,t_1]} = \tilde{\gamma}_1,$$

hence this **lift** is unique. Now, we see that we can simply repeat this argument, namely replacing t_i by t_{i+1} , $\tilde{\gamma}_i(t_i)$ by $\tilde{\gamma}_{i+1}(t_{i+1})$ and so on. Since this partition is finite, hence in finitely many steps, we obtain a unique **path homotopy** $\tilde{\gamma}$ by concatenating all $\tilde{\gamma}_i$ starting at \tilde{x}_0 .

Lifting a path homotopy. We now consider lifting a **path homotopy**. Consider

$$\gamma_1 \simeq_{\tilde{F}} \gamma_2 \text{ rel}\{0, 1\}$$

we'll show that $\tilde{\gamma}_1 \simeq_{\tilde{F}} \tilde{\gamma}_2 \text{ rel}\{0, 1\}$ where $p \circ \tilde{F} = F$. Firstly, we denote $x_0 := \gamma_1(0) = \gamma_2(0)$, such that



We claim that it's sufficient to show that there exists a continuous $\tilde{F}: I \times I \rightarrow X$ such that $p \circ \tilde{F} = F$, and $\tilde{F}(\{0\} \times I) = x_0$. It's because

$$p \circ \tilde{F}_0 = F_0 = \gamma_1, \quad p \circ \tilde{F}_1 = F_1 = \gamma_2$$

where \tilde{F}_0, \tilde{F}_1 is γ_1, γ_2 's **lifting** starting at \tilde{x}_0 , respectively. And since $p \circ \tilde{F} = F$, we have

$$p\left(\tilde{F}(\{1\} \times I)\right) = x_1 \Rightarrow \tilde{F}(\{1\} \times I) \subset p^{-1}(\{x_1\}),$$

which implies $\exists \tilde{x}_1 \in p^{-1}(\{x_1\})$ such that $\tilde{F}(\{1\} \times I) = \tilde{x}_1$ since we know that $p^{-1}(\{x_1\})$ is a discrete points-set and \tilde{F} is assumed to be continuous, and $\{1\} \times I$ is connected. We now show \tilde{F} exists.

We define

$$\begin{aligned} \tilde{F}: I \times I &\rightarrow X \\ (s, t) &\mapsto \tilde{F}_t(s), \end{aligned}$$

where $\tilde{F}_t: [0, 1] \rightarrow \tilde{X}$ is a **lift** starting at \tilde{x}_0 of $F_t: [0, 1] \rightarrow X, s \mapsto F(s, t)$. Obviously, $p \circ \tilde{F} = F$ from the uniqueness of the **lift** of a path, and also, $\tilde{F}(\{0\} \times I) = \tilde{x}_0$ holds trivially, hence we only need to show \tilde{F} is continuous.

- (1) We show that $\exists \epsilon_0 > 0$ such that $\tilde{F}|_{[0, \epsilon_0] \times I}$ is continuous.



Since F is continuous, we see that there exists an open neighborhood U_{x_0} of x_0 such that $p^{-1}(U_{x_0}) = \coprod_{\alpha} U_{x_0 \alpha}$, where

$$p|_{U_{x_0 \alpha}} : U_{x_0 \alpha} \xrightarrow{\cong} U_{x_0}.$$

Since $F^{-1}(U_{x_0})$ is an open set contain $\{0\} \times I$, there exists a $\epsilon_0 > 0$ such that $[0, \epsilon_0] \times I \subset F^{-1}(U_{x_0})$,^b which implies

$$F([0, \epsilon_0] \times I) \subset U_{x_0}.$$

Note that $x_0 \in U_{x_0}$ and $p(\tilde{x}_0) = x_0$, we may assume $\tilde{x}_0 \in U_{x_0 \alpha_1}$. Consider $(p|_{U_{x_0 \alpha_1}})^{-1} \circ F|_{[0, \epsilon_0] \times I}$, which is a [lift](#) of $F|_{[0, \epsilon_0] \times I}$. We claim that

$$(p|_{U_{x_0 \alpha_1}})^{-1} \circ F|_{[0, \epsilon_0] \times I} = \tilde{F}|_{[0, \epsilon_0] \times I}.$$

This is because for every $t \in I$,

$$s \mapsto (p|_{U_{x_0 \alpha_1}})^{-1} \circ F|_{[0, \epsilon_0] \times I}(s, t)$$

is a [lift](#) starting at \tilde{x}_0 ; also, for every $t \in I$,

$$s \mapsto \tilde{F}|_{[0, \epsilon_0] \times I}(s, t)$$

is a [lift](#) of F_t starting at \tilde{x}_0 . From the uniqueness of the [lift](#) of [paths](#), we see that they're equal. Note that this implies \tilde{F} is now continuous at $[0, \epsilon_0] \times I$, since F is continuous and $p|_{U_{x_0 \alpha_1}}$ is a homeomorphism, hence continuous, then from

$$\tilde{F}|_{[0, \epsilon_0] \times I} = \underbrace{(p|_{U_{x_0 \alpha_1}})^{-1}}_{\text{continuous}} \circ \underbrace{F|_{[0, \epsilon_0] \times I}}_{\text{continuous}},$$

we see that \tilde{F} is indeed continuous at $[0, \epsilon_0] \times I$.

- (2) We now prove that $\tilde{F}: I \times I \rightarrow \tilde{X}$ is continuous. Assume there exists $(s_0, t_0) \in I \times I$ such that \tilde{F} is discontinuous at (s_0, t_0) . Then consider

$$0 < \epsilon_0 \leq \inf \underbrace{\left\{ s \mid \tilde{F} \text{ is discontinuous at } s, t_0 \right\}}_{\ni s_0 \Rightarrow \neq \emptyset} =: s_1,$$

where the first inequality is from the first step.



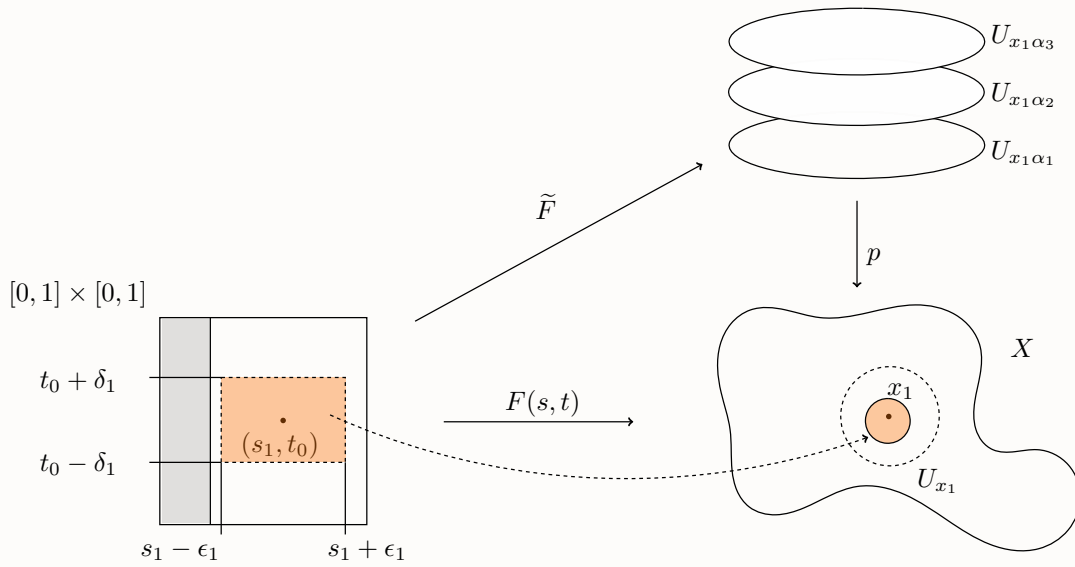
Let $x_1 := F(s_1, t_0)$, $\tilde{x}_1 := \tilde{F}(s_1, t_0)$, then there exists an open neighborhood U_{x_1} in X such that $x_1 \in U_{x_1} = \coprod_{\alpha} U_{x_1\alpha}$, where

$$p|_{U_{x_1\alpha}} : U_{x_1\alpha} \xrightarrow{\cong} U_{x_1}.$$

Since F is continuous, there exists an $\epsilon_1 > 0$, $\delta_1 > 0$ such that

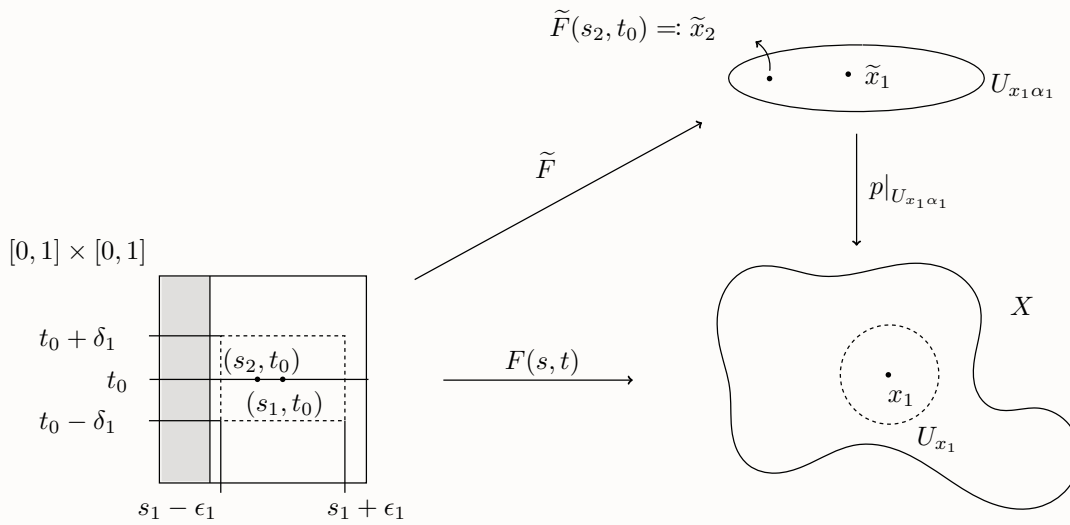
$$F((s_1 - \epsilon_1, s_1 + \epsilon_1) \times (t_0 - \delta_1, t_0 + \delta_1)) \subset U_{x_1}.$$

Notice that here we're considering **open** box.



We may assume $\tilde{x}_1 \in U_{x_1\alpha_1}$. Then, we see that \tilde{F}_{t_0} is a **lift** of F_{t_0} , which means \tilde{F}_{t_0} is continuous, hence there exists an s_2 such that $s_1 - \epsilon_1 < s_2 < s_1$ such that

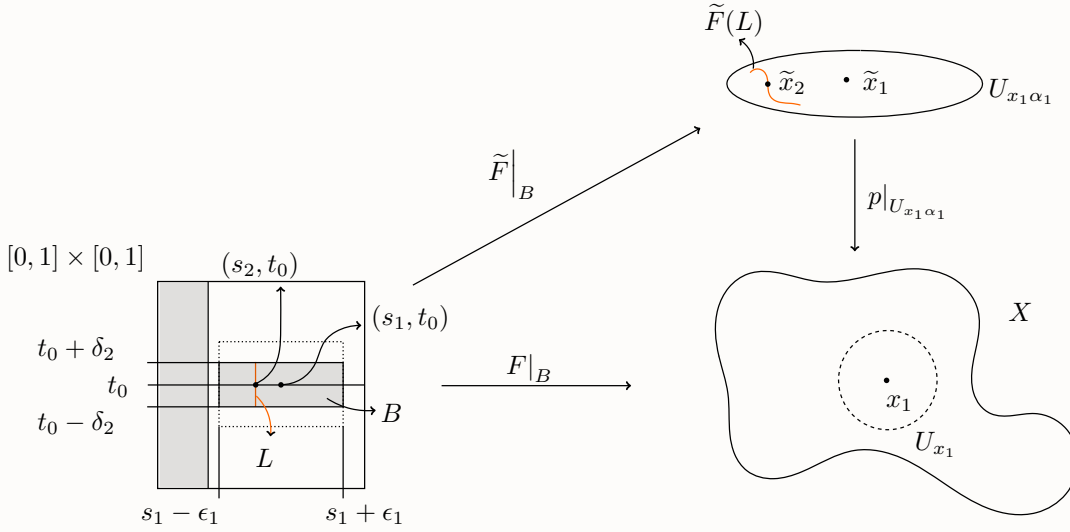
$$\tilde{F}(s_2, t_0) \in U_{x_1\alpha_1}.$$



We see that \tilde{F} is continuous at (s_2, t_0) , hence there exists a $\delta_2 > 0$ such that

$$\tilde{F}(\{s_2\} \times (t_0 - \delta_2, t_0 + \delta_2)) \subset U_{x_1\alpha_1}.$$

Note that here we can also consider a closed interval, which matches what we're going to do. Namely, we're going to construct a **closed** box B . But this is just a technical detail.



Now, observe that $\tilde{F}(B) \subset U_{x_1\alpha_1}$. To see this, consider a fixed $t \in (t_0 + \delta_2, t_0 - \delta_2)$, then the map \tilde{F} is

$$[s_1 - \epsilon_1, s_1 + \epsilon_1] \rightarrow \tilde{X}, \quad s \mapsto \tilde{F}(s, t) = \tilde{F}_t(s).$$

Specifically,

$$\tilde{F}_t([s_1 - \epsilon_1, s_1 + \epsilon_1]) \subset p^{-1}(U_{x_1}) = \coprod_{\alpha} U_{x_1\alpha},$$

with the fact that $\tilde{F}_t([s_1 - \epsilon_1, s_1 + \epsilon_1])$ is connected, and $\tilde{F}_t(s_2) \in U_{x_1\alpha_1}$ with \tilde{F}_t is a [lift](#) of F_t , hence continuous, so

$$\tilde{F}_t([s_1 - \epsilon_1, s_1 + \epsilon_1]) \subset U_{x_1\alpha_1}.$$

This is true for every $t \in [t_0 - \delta_2, t_0 + \delta_2]$, hence $\tilde{F}|_B \subset U_{x_1\alpha_1}$. Now, since

$$p|_{U_{x_1\alpha_1}} \circ \tilde{F}|_B = F|_B,$$

and

$$\left(p|_{U_{x_1\alpha_1}}\right)^{-1} \circ F|_B : B \rightarrow U_{x_1\alpha_1},$$

so

$$p|_{U_{x_1\alpha_1}} \circ \left(\left(p|_{U_{x_1\alpha_1}}\right)^{-1} \circ F|_B\right) = F|_B$$

obviously. Since $p|_{U_{x_1\alpha_1}}$ is a homeomorphism, we have

$$\tilde{F}|_B = \underbrace{\left(p|_{U_{x_1\alpha_1}}\right)^{-1}}_{\text{continuous}} \circ \underbrace{F|_B}_{\text{continuous}},$$

hence we have $\tilde{F}|_B$ is continuous, which leads to a contradiction since

$$s_1 = \inf \left\{ s \mid \tilde{F} \text{ is discontinuous at } s, t_0 \right\},$$

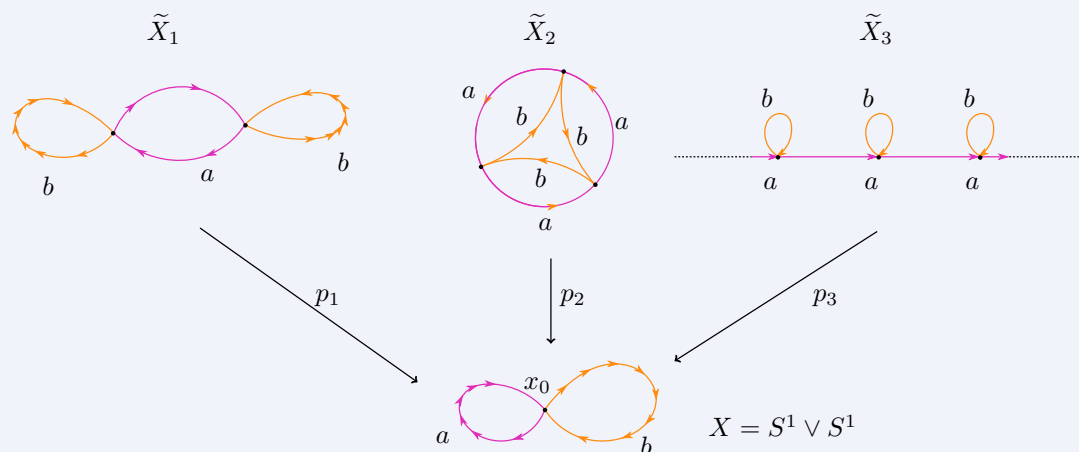
while \tilde{F} is continuous for all B , hence we see that $\tilde{F} : I \times I \rightarrow \tilde{X}$ is continuous.^c

^ahttps://en.wikipedia.org/wiki/Lebesgue%27s_number_lemma

^bNotice that we're working on product topology here.

^cThere is a tricky situation, namely while $s_1 = 1$. But this can be considered also.

Example (Covers of $S^1 \vee S^1$). We have the following covers of $S^1 \vee S^1$.



Note that in each cover (those three on the top), the black dot is the preimage of $\{x_0\}$, namely $p_i^{-1}(\{x_0\})$.

Remark. We see that for each $p_i^{-1}(\{x_0\})$, there are exactly

- one a edge goes out
- one b edge goes out
- one a edge goes in
- one b edge goes in

It turns out that there are much more covers of $S^1 \vee S^1$, as long as this main property is satisfied.

Proposition 4.1.2. Let $p: (\tilde{X}, \tilde{x}_0) \rightarrow (X, x_0)$ be a covering map. Then

- (1) $p_*: \pi_1(\tilde{X}, \tilde{x}_0) \rightarrow \pi_1(X, x_0)$ is injective.
- (2) $p_*(\pi_1(\tilde{X}, \tilde{x}_0)) \subseteq \pi_1(X, x_0)$, which picks out the subset

$$\{[\gamma] \mid \text{lift } \tilde{\gamma} \text{ starting at } \tilde{x}_0 \text{ is a loop.}\}.$$

Proof. We prove this one by one.

- (1) Suppose $\tilde{\gamma} \in \pi_1(\tilde{X}, \tilde{x}_0)$ is in $\ker(p_*)$. Then

$$[\gamma] = p_*([\tilde{\gamma}]) = [p \circ \tilde{\gamma}].$$

Let γ_t be a nullhomotopy from γ to the constant loop $c_{x_0} \text{ rel } \{0, 1\}$. We can then lift γ_t to $\tilde{\gamma}_t$ where $\tilde{\gamma}_0 = \tilde{\gamma}$. Now, we claim that

- $\tilde{\gamma}$ is a **homotopy** $\text{rel}\{0, 1\}$.
- $\tilde{\gamma}_1$ is the **constant loop** $c_{\tilde{x}_0}$.

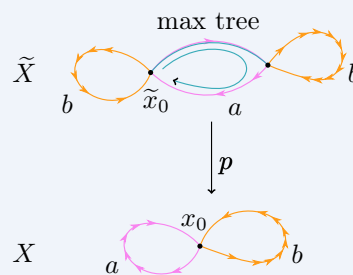
$$\begin{array}{ccc} & \tilde{X} & \\ \tilde{\gamma} \nearrow & \downarrow p & \\ I & \xrightarrow{\gamma} & X \end{array} \quad \begin{array}{ccc} & \tilde{X} & \\ \tilde{\gamma}_t \nearrow & \downarrow p & \\ I \times I & \xrightarrow{\gamma_t} & X \end{array}$$

We see that the above diagrams prove the first claim, since we know that the left and right edge of $I \times I$ maps to x_0 under γ_t , and $c_{\tilde{x}_0}$ **lifts** this, so by uniqueness $t \mapsto \tilde{\gamma}_t(0)$ and $t \mapsto \tilde{\gamma}_t(1)$ must be constant **paths** at \tilde{x}_0 as desired.

Then the **lift** $\tilde{\gamma}_t$ is a **homotopy of paths** to the constant loop, so $[\tilde{\gamma}] = 1$.

(2) Let see an example to show the idea of the proof.

Example. Given



Then

$$p_*\pi_1 = \langle b, a^2, ab\bar{a} \rangle \subseteq \pi_1(X) = \langle a, b \mid \rangle.$$

Proposition 4.1.3 (Lifting criterion). Let $p: (\tilde{Y}, \tilde{y}_0) \rightarrow (Y, y_0)$ be a **covering map**. Given

- $f: (X, x_0) \rightarrow (Y, y_0)$;
- X is **path**-connected, locally **path**-connected,

then a **lift**

$$\tilde{f}: (X, x_0) \rightarrow (\tilde{Y}, \tilde{y}_0)$$

exists if and only if

$$f_*(\pi_1(X, x_0)) \subseteq p_*(\pi_1(\tilde{Y}, \tilde{y}_0)).$$

In diagram, we have

$$\begin{array}{ccc} & (\tilde{Y}, \tilde{y}_0) & \\ \exists \tilde{f} \nearrow & \downarrow p & \\ (X, x_0) & \xrightarrow{f} & (Y, y_0) \end{array} \quad \begin{array}{ccc} & \pi_1(\tilde{Y}, \tilde{y}_0) & \\ \tilde{f}_* \nearrow & \downarrow p_* & \\ \pi_1(X, x_0) & \xrightarrow{f_*} & \pi_1(Y, y_0) \end{array}$$

Lecture 15: Lifting

Before proving **Proposition 4.1.3**, we first see an application.

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Example. Every continuous map $f: \mathbb{R}P^2 \rightarrow S^1$ is **nullhomotopic**.

Proof. If we can show that there is a **lift** $\tilde{f}: \mathbb{R}P^2 \rightarrow \mathbb{R}$ of f , then we're done since we can apply the **straight line nullhomotopy** on \mathbb{R} , i.e.,

$$\begin{array}{ccc} & & \mathbb{R} \\ & \nearrow \tilde{f} & \downarrow p \\ \mathbb{R}P^2 & \xrightarrow{f} & S^1 \end{array}$$

and consider $f = p \circ \tilde{f}$ compose **nullhomotopy** with p , so $f \simeq$ constant map. Specifically, since $\pi_1(\mathbb{R}P^2) = \mathbb{Z}/2\mathbb{Z}$ and $\pi_1(S^1) = \mathbb{Z}$, hence

$$f_*(\pi_1(\mathbb{R}P^2)) = 0$$

since \mathbb{Z} has no (nonzero) **torsion**. So it **lifts** by **Proposition 4.1.3**. *

Now we can proof **Proposition 4.1.3**.

Proof of Proposition 4.1.3. We prove two directions as follows.

Necessary. We see that we can **factorize** f_* as

$$f_* = p_* \circ \tilde{f}_*$$

follows from the **functoriality** of π_1 .

Sufficient. Let $x \in X$. Choose a **path** γ from x_0 to x by the assumption that X is **path-connected**. Then, $f\gamma$ has a unique **lift** starting at \tilde{y}_0 , denote by $\tilde{f}\gamma$. Now, define

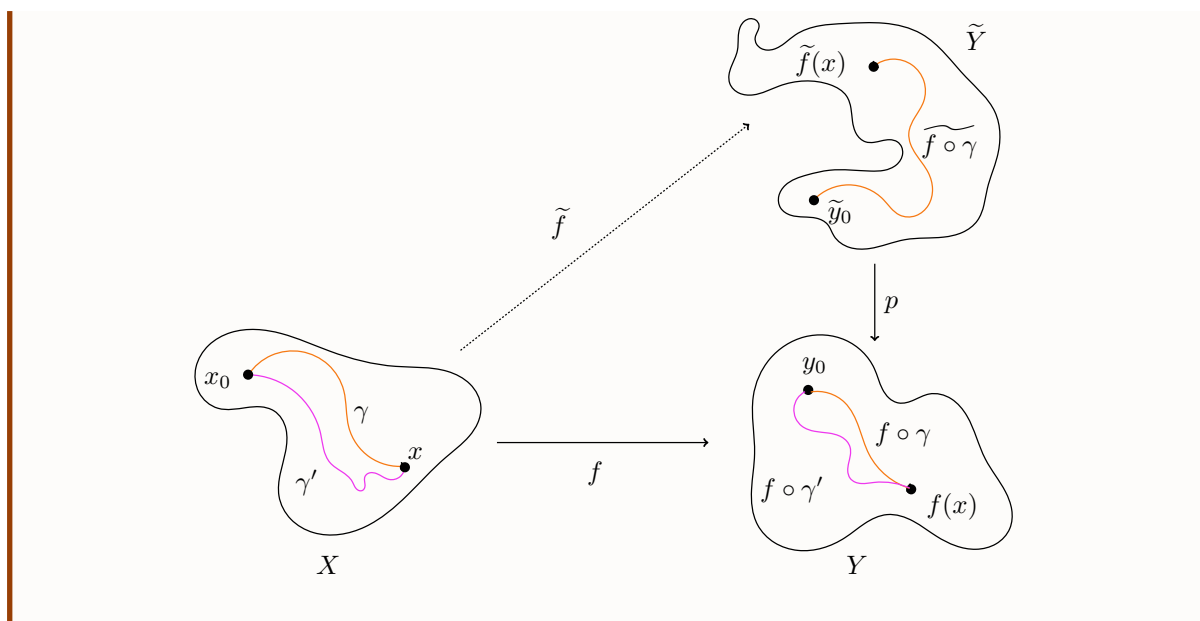
$$\tilde{f}(x) = \tilde{f}\gamma(1).$$

Then, we need to check

- (1) \tilde{f} is well-defined. Suppose γ, γ' are **paths** in X from x_0 to x . We want to show

$$\widetilde{f\gamma'}(1) = \widetilde{f\gamma}(1).$$

Since $\gamma \cdot \overline{\gamma'}$ is a loop in X at x_0 , we know that $[(f\gamma) \cdot (\overline{f\gamma'})]$ is a class of loops in Y in $\text{Im}(f_*)$. By hypothesis, this class of loops is in $\text{Im}(p_*)$. It **lifts** to a loop which is based at \tilde{y}_0 . By uniqueness of **lifts**, this loop lifting $(f\gamma) \cdot (\overline{f\gamma'})$ to \tilde{Y} must be equal to the **lifts** $\tilde{f}\gamma \cdot \overline{\tilde{f}\gamma'}$ with a common value at $t = 1/2$. Hence, $\tilde{f}\gamma(1) = \tilde{f}\gamma'(1)$ as desired, namely the endpoints agree.

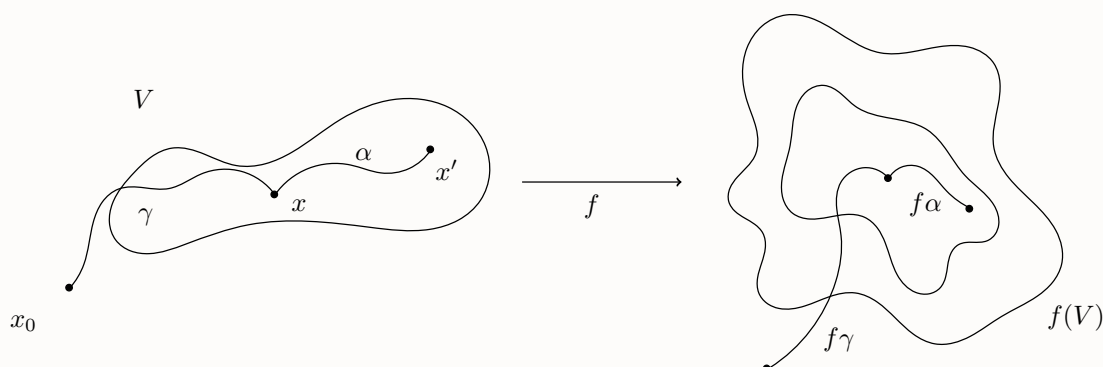


Lecture 16: Proving Proposition 4.1.3

We now continue our proof of Proposition 4.1.3.

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2. \tilde{f} is continuous. Choose $x \in X$ and a neighborhood \tilde{U} of $\tilde{f}(x)$ in \tilde{Y} . Note that we can choose \tilde{U} small enough to $p|_{\tilde{U}}$ is homeomorphism to U in Y . Now, there exists a neighborhood V of x in X with $f(V) \subseteq U$.



The goal is $\tilde{f}(V) \subseteq \tilde{U}$. Without loss of generality, we can assume that V is path-connected. Then,

$$\tilde{f}\gamma \cdot \tilde{f}\alpha = [\tilde{f}\gamma \cdot \tilde{f}\alpha].$$

Hence,

$$\tilde{f}\alpha = (p|_{\tilde{U}})^{-1} \circ f \circ \alpha,$$

where $(p|_{\tilde{U}})^{-1}$'s image is in \tilde{U} , so

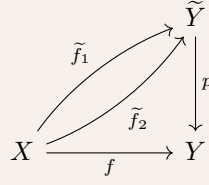
$$\tilde{f}(x') = f\gamma \cdot f\alpha(1) \in \tilde{U},$$

which implies

$$\tilde{f}(V) \subseteq \tilde{U}.$$

■

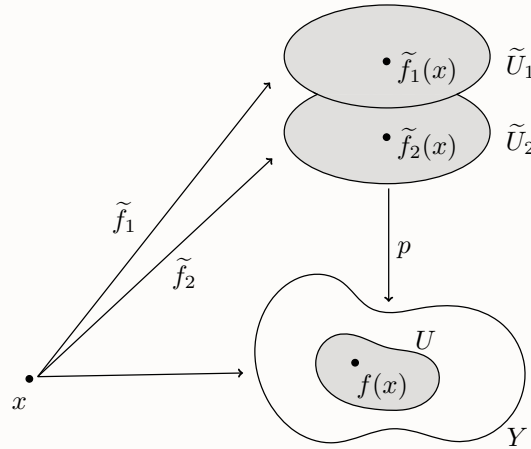
Proposition 4.1.4 (Uniqueness of lifts). Let $p: \tilde{Y} \rightarrow Y$ be a covering map with X is a connected space. If two lifts \tilde{f}_1, \tilde{f}_2 of the same map f agree at a single point, then they agree everywhere.



Proof. Let S being

$$S := \{x \in X \mid \tilde{f}_1(x) = \tilde{f}_2(x)\}.$$

We want to show that S is both closed and open, so if S is nonempty, $S = X$.



We see that \tilde{U}_1 and \tilde{U}_2 are slices of $p^{-1}(U)$, where U is an evenly covered neighborhood of $f(x)$.

- (1) If $\tilde{f}_1(x) \neq \tilde{f}_2(x)$. Then \tilde{U}_1, \tilde{U}_2 are disjoint. Since \tilde{f}_1, \tilde{f}_2 are continuous, there exists a neighborhood N of x with

$$\tilde{f}_1(N) \subseteq \tilde{U}_1, \quad \tilde{f}_2(N) \subseteq \tilde{U}_2,$$

with the fact that they're disjoint, so x is an interior point of S^c .

- (2) If $\tilde{f}_1(x) = \tilde{f}_2(x)$. Then $\tilde{U}_1 = \tilde{U}_2$. Choose N as before, then we have

$$\tilde{f}_1(n) = (p|_{\tilde{U}_1})^{-1}(f(n)) = \tilde{f}_2(n),$$

hence $x \in \text{Int}(S)$.

■

4.2 Deck Transformation

We now want to introduce a special kind of transformation.

Definition 4.2.1 (Isomorphism of covers). Given covering maps

$$p_1: \tilde{X}_1 \rightarrow X, \quad p_2: \tilde{X}_2 \rightarrow X,$$

an *isomorphism of covers* is a homeomorphism $f: \tilde{X}_1 \rightarrow \tilde{X}_2$ such that $p_1 = p_2 \circ f$.

$$\begin{array}{ccc} \tilde{X}_1 & \xrightarrow{f} & \tilde{X}_2 \\ & \searrow p_1 & \swarrow p_2 \\ & X & \end{array}$$

Exercise. This defines equivalent relation on *covers* of X .

Definition 4.2.2 (Deck transformation). Given a *covering map* $p: \tilde{X} \rightarrow X$, the *isomorphisms of covers* $\tilde{X} \rightarrow \tilde{X}$ are called *deck transformation*.

Definition 4.2.3 (Set of deck transformation). Also, we let $G(\tilde{X})$ denotes the *set of deck transformations*.

Note. Note that we've suppressed the data of p in the notation, but this data is essential to what a *deck transformation* is, when this is unclear we write $G(\tilde{X}, p)$.

Lecture 17: Deck Transformation

Example. *Deck transformations* $G(\tilde{X})$ are a subgroup of the group of homeomorphisms of \tilde{X} .

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Example. Given the *cover* $p: \mathbb{R} \rightarrow S^1$.

- *Deck maps*: translation by $n \in \mathbb{Z}$ units.
- $G(\mathbb{R}) \cong \mathbb{Z}$

Example. Given the *cover* $p_n: S^1 \rightarrow S^1$ be an n -sheeted *cover*.

- *Deck maps*: rotation by $2\pi/n$.
- $G(S^1, p_n) \cong \mathbb{Z} / n\mathbb{Z}$

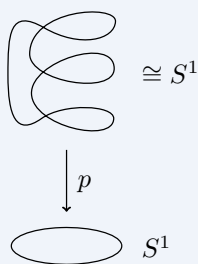


Figure 4.1: $p_n: S^1 \rightarrow S^1$ be an n -sheeted *cover*, here $n = 3$.

Exercise (Deck Transformation is determined by the image of one point). Given X, \tilde{X} are *path-connected*, locally *path-connected*, *deck map* is determined by the image of any one point.

Answer.

$$\begin{array}{ccc} & & \tilde{X} \\ & \nearrow f & \downarrow p \\ \tilde{X} & \xrightarrow{p} & X \end{array}$$

⊛

Corollary 4.2.1. If a **deck transformation** has a fixed point, it is the identity transformation.

Exercise. Let X be connected. Given a **deck transformation** $\tau: \tilde{X} \rightarrow \tilde{X}$, τ defines a permutation of $p^{-1}(\{x_0\})$. If this permutation has a fixed point, then it is the identity.

Definition 4.2.4 (Regular (normal) cover). A **covering space** $p: \tilde{X} \rightarrow X$ is *regular* or *normal* if $\forall x_0 \in X, \forall \tilde{x}_0, \tilde{x}_1 \in p^{-1}(\{x_0\})$, there exists a **deck transformation** such that

$$\tilde{x}_0 \mapsto \tilde{x}_1.$$

Example (Regular and non-regular cover of $S^1 \vee S^1$). Given the following **covers** of $S^1 \vee S^1$, determine which cover is **regular**.



Proof. The left one is **regular**, while the right one is not since there is no automorphism from \tilde{x}_0 to \tilde{x}_1 or \tilde{x}_2 . ⊛

Remark. A **regular cover** is *as symmetric as possible*.

Exercise. **Regular** means that the group $G(\tilde{X})$ acts transitively on $p^{-1}(\{x_0\})$. Explain why we cannot ask for more than this:

$G(\tilde{X})$ cannot induce the full symmetric group on $p^{-1}(\{x_0\})$ provided that $|p^{-1}(\{x_0\})| > 2$.

Answer. The key is uniqueness. ⊛

Since we're talking about symmetric, it's natural to introduce the following concept for groups.

Definition 4.2.5 (Normal subgroup). A subgroup N of G is called a *normal subgroup* if it's invariant under conjugation, and we denote this relation as $N \triangleleft G$.

Definition 4.2.6 (Normalizer). Given G as a group, $H \subseteq G$ is a subgroup of G . Then the *normalizer* of H , denoted by $N(H)$, is defined as

$$N(H) := \{g \in G \mid gH = Hg\}.$$

Exercise. We can prove the followings.

- (1) $N(H)$ is a subgroup.

- (2) $H \leq N(H)$.
- (3) H is normal in $N(H)$.
- (4) If $H \leq G$ is normal, $N(H) = G$.
- (5) $N(H)$ is the largest subgroup (under containment) of G containing H as normal subgroup.

Proposition 4.2.1. Given $p: (\tilde{X}, \tilde{x}_0) \rightarrow (X, x_0)$ be a cover, and \tilde{X}, X are path-connected, locally path-connected. Let

$$H = p_*(\pi_1(\tilde{X}, \tilde{x}_0)) \subseteq \pi_1(X, x_0).$$

Then

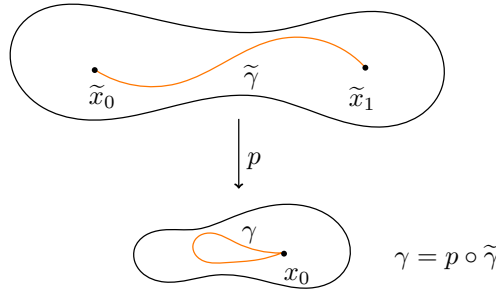
- (1) p is normal if and only if $H \subseteq \pi_1(X, x_0)$ is normal.
- (2) We have

$$G(\tilde{X}) \cong N(H) / H,$$

where $G(\tilde{X})$ are deck maps, and $N(H)$ is the normalizer of H in $\pi_1(X, x_0)$.

Remark. A fact is worth noting is the following. Let $\tilde{\gamma}$ be a path \tilde{x}_0 to \tilde{x}_1 . Then

$$p_*(\pi_1(\tilde{X}, \tilde{x}_0)) = [\gamma]p_*(\pi_1(\tilde{X}, \tilde{x}_1))[\gamma^{-1}].$$



Lecture 18: Proving Proposition 4.2.1

Now let's prove Proposition 4.2.1.

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Proof of Proposition 4.2.1. Let X, x_0 be the base space and $\tilde{x}_0, \tilde{x}_1 \in p^{-1}(\{x_0\})$ where $p: \tilde{X} \rightarrow X$ is a covering map. Further, let $H := p_*(\pi_1(\tilde{X}, \tilde{x}_0))$.

In homework, given $(X, x_0), \tilde{x}_0, \tilde{x}_1 \in p^{-1}(\{x_0\})$ if we change the basepoint from $\pi_1(\tilde{X}, \tilde{x}_0)$ to $\pi_1(\tilde{X}, \tilde{x}_1)$, then we have the induced subgroups of the base spaces fundamental group are conjugate by some loop $[\gamma] \in \pi_1(X, x_0)$, i.e.,

$$p_*(\pi_1(\tilde{X}, \tilde{x}_1)) = [\gamma] \cdot p_*(\pi_1(\tilde{X}, \tilde{x}_0)) \cdot [\gamma]^{-1}$$

where γ is lifted to a path from \tilde{x}_0 to \tilde{x}_1 .

Therefore, $[\gamma] \in N(H)$ if and only if $p_*(\pi_1(\tilde{X}, \tilde{x}_1)) = p_*(\pi_1(\tilde{X}, \tilde{x}_0))$, and this holds if and only if there is a deck transformation taking \tilde{x}_0 to \tilde{x}_1 by the classification of based covering spaces in the homework.

Note. Alternatively, we can use the lifting criterion.

This shows that p is a normal cover if and only if H is normal, which proves the first claim.

We then define a map Φ such that

$$\Phi: N(H) \rightarrow G(\tilde{X})[\gamma], \quad \cdot \mapsto \tau$$

where τ **lifts** to a **path** from \tilde{x}_0 to \tilde{x}_1 and τ is a **deck transformation** mapping \tilde{x}_0 to \tilde{x}_1 , which will be uniquely defined by the uniqueness of **lifts** with specified base points. We now need to check

- (1) Φ is surjective.
- (2) $\ker(\Phi) = H$.
- (3) Φ is a group homomorphism.

If we can prove all the above, then the result follows directly from the first isomorphism theorem.

- (1) We've proved that Φ is surjective before in our work above.
- (2) $\Phi([\gamma])$ is the identity if and only if τ sends \tilde{x}_0 to \tilde{x}_0 , meaning that $[\gamma]$ **lifts** to a loop. Then by our characterization of the **fundamental group** downstairs:

$$\ker(\Phi) = \{[\gamma] \mid [\gamma] \text{ lifts to a loop}\} = H.$$

- (3) Suppose we have loops $[\gamma_1] \xrightarrow{\Phi} \tau_1$ and $[\gamma_2] \xrightarrow{\Phi} \tau_2$. We claim that $\gamma_1 \cdot \gamma_2$ **lifts** to $\tilde{\gamma}_1 \cdot \tau(\tilde{\gamma}_2)$.



Exercise. Check that the **lift** of γ_2 starting at \tilde{x}_1 is exactly $\Phi_1(\tilde{\gamma}_2)$, where $\tilde{\gamma}_2$ is a **lift** starting at \tilde{x}_0 .



Figure 4.2: Must be **lift** of γ' starting at \tilde{x}_2

Answer. The key is the uniqueness of **lifts**. ⊗

We then just observe that this **path** $\tilde{\gamma}_1 \cdot \tau_1(\tilde{\gamma}_2)$ is a **path** from \tilde{x}_0 to $\gamma_1(\tilde{\gamma}_2(1)) = \tau_1(\tau_2(\tilde{x}_0))$, so the image must be a **deck transformation** sending \tilde{x}_0 to $\tau_1(\tau_2(\tilde{x}_0))$. But then $\tau_1 \circ \tau_2$ maps \tilde{x}_0 to this same point, and from **this exercise**, we know that the **deck transformations** are determined by where they send a single point, hence we're done. ■

Corollary 4.2.2. If p is a normal covering, then $G(\tilde{X}) \cong \pi_1(X, x_0) / H$.

Definition 4.2.7 (Universal covering). A cover $p: \tilde{X} \rightarrow X$ is called a *universal covering* if \tilde{X} is simply connected.

Corollary 4.2.3. If \tilde{X} is the universal cover, then $G(\tilde{X}) \cong \pi_1(X, x_0)$.

Exercise. Whether $\text{Im}(p_*)$ is normal is independent of the basepoint in \tilde{X} and X .

So, p is normal if and only if $G(\tilde{X})$ is transitive on $p^{-1}(x_0)$ for at least one $x_0 \in X$.

Exercise. Let Σ_g be the genus g surface. Prove that Σ_g has a normal n -sheeted path-connected cover for every n .

Chapter 5

Homology

Homology is a general way of associating a sequence of algebraic objects, such as **Abelian groups** or modules, with other mathematical objects such as topological spaces. In this section, we'll develop this notion rigorously, and make some connection with **fundamental group** to see why this is much more powerful.

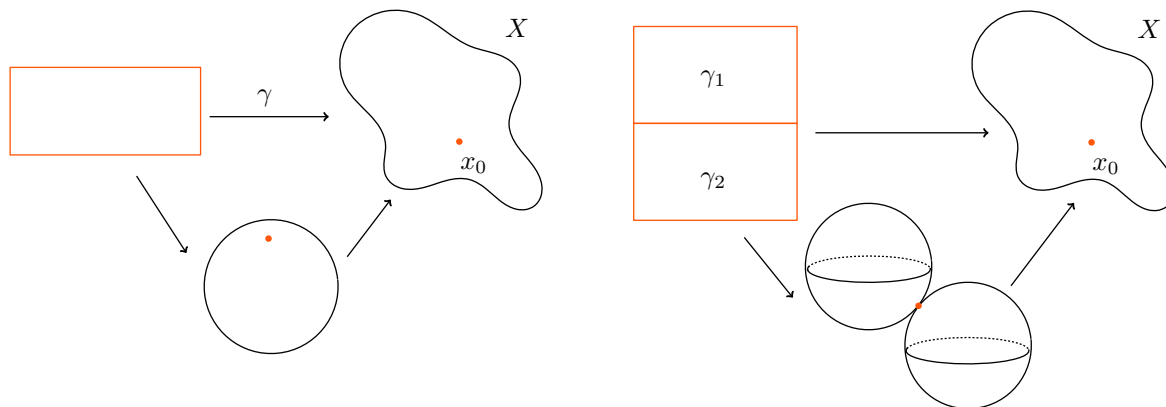
Lecture 19: Simplex and Homology

5.1 Motivation for Homology

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Informally, the higher **homotopy** groups is defined as

$$\pi_n(X, x_0): I_*^n \rightarrow (X, x_0), \quad \partial I^n \mapsto x_0.$$



We see that it's extremely hard to compute higher **fundamental group**. Hence instead, we will study the higher dimensional structure of X via *homology*.

- **Cons.**
 - The definition is more opaque at first encounter.
- **Pros.**
 - Lots of computational tools
 - Functional
 - **Abelian Groups**

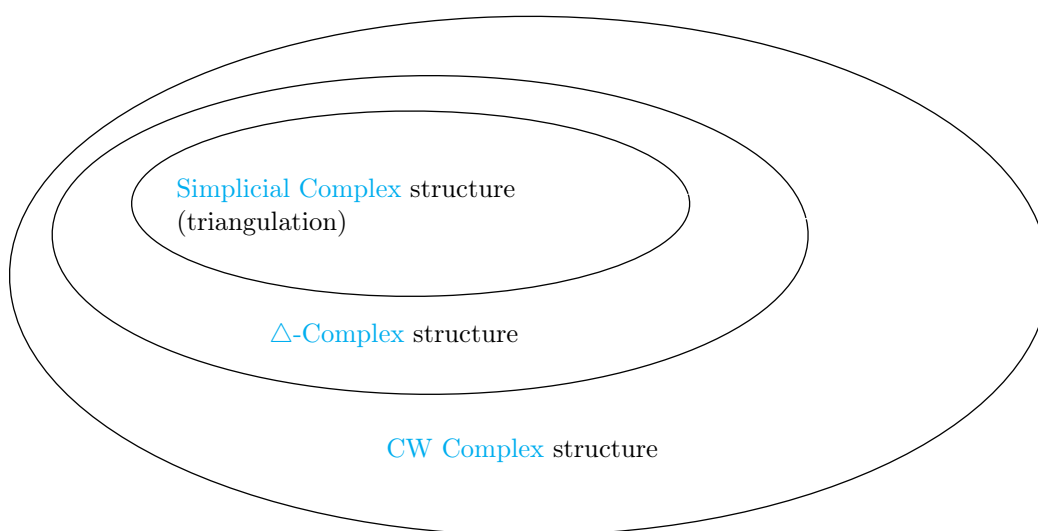
Remark. More like π_n for $n > 1$.

- No basepoints
- Can compute using **CW** structure.
- Good properties. For example, $H_n = 0$ if $n > \dim X$

5.2 Simplicial Homology

5.2.1 Δ -Simplex

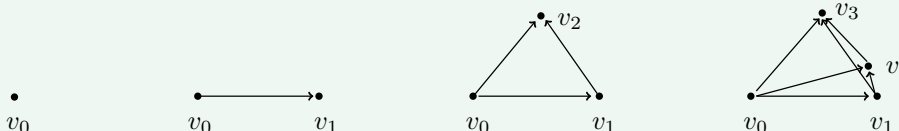
This is a stricter version of a **CW complex** which allows us to decompose our spaces into **cells**. In terms of how things fit together, we have the following diagram.



Now we try to give the definition.

Definition 5.2.1 (Simplex). We see that

- *0-simplex*. A point.
- *1-simplex*. Interval.
- *2-simplex*. Triangle.
- *3-simplex*. Tetrahedron.
- *n-simplex*. The convex hull of $(n + 1)$ -points position in \mathbb{R}^n .



Remark. We see that

- The top of which is the 2-disk and remember **cell** structure (edges and vertices) and remember orientation (ordering on vertices).

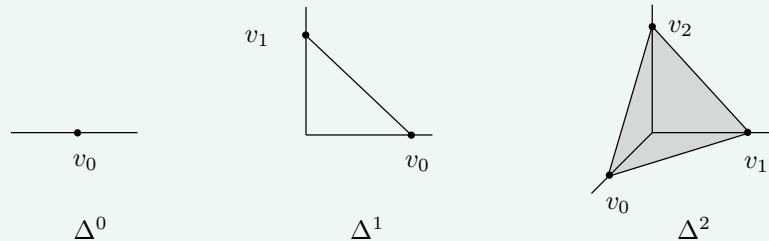
- The top of which is the 3-disk and [cells](#) and the orientation.
- We can view [simplices](#) as both *combinatorial* and *topological* objects.

An alternative definition can be made.

Definition 5.2.2 (Standard simplex). We say that an n -dimensional *standard simplex*, denoted by Δ^n is

$$\Delta^n = \left\{ (t_0, \dots, t_n) \in \mathbb{R}^{n+1} \mid t_i \geq 0, \sum_i t_i = 1 \right\}.$$

We'll call such a simplex as *standard n -simplex*.



Remark. In our definition, the [standard simplices](#) will implicitly come with a choice of ordering of the vertices as

$$\Delta^n = [v_0, v_1, \dots, v_n]$$

such that the convex hull of these points is taken with this ordering.

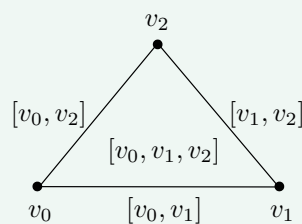
Lecture 20: Simplicial Complex

We now give some definitions about [standard simplex](#).

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Definition. With [Definition 5.2.2](#), we have the followings.

Definition 5.2.3 (Subsimplex). Combinatorially, a *subsimplex* of a [simplex](#) Δ^n is a subset of the vertices; while topologically, it's the convex hull of the subset of vertices.



Definition 5.2.4 (Face). A *face* of a [simplex](#) Δ^n is a [subsimplex](#) of 1 dimensional lower than Δ^n (codimension 1).

Definition 5.2.5 (Boundary). The *boundary* $\partial\sigma$ of a [simplex](#) σ is the union of its [faces](#).

Definition 5.2.6 (Open simplex). The *open simplex* of Δ is defined as

$$\mathring{\Delta}^n := \Delta^n - \partial\Delta^n.$$

Definition 5.2.7 (Δ -Complex). A Δ -complex structure on X is a collection of maps

$$\sigma_\alpha: \Delta^n \rightarrow X$$

such that

- (1) $\sigma_\alpha|_{\mathring{\Delta}^n}$ injective, each point of X is in the image of exactly one such map.
- (2) Each restriction of σ_α to a **face** coincides with a map

$$\sigma_\beta: \Delta^{n-1} \rightarrow X.$$

- (3) A set $A \subseteq X$ is open if and only if $\sigma_\alpha^{-1}(A)$ is open in $\mathring{\Delta}^n$ for all σ_α , i.e., X is a **quotient**

$$\coprod_{n,\alpha} \Delta_\alpha^n \xrightarrow{\coprod \sigma_\alpha} X.$$

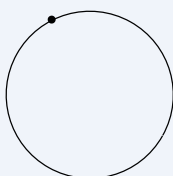
Exercise. A Δ -complex X is a **CW complex** W with characteristic maps σ_α with extra constraints on the **attaching maps**.

Note. We see that the second condition of **Definition 5.2.7** implies that **attaching maps** injective on interior of **faces**.

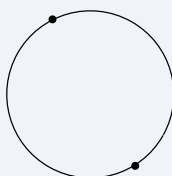
Definition 5.2.8 (Simplicial complex). A *simplicial complex* is a Δ -complex such that

- σ_α must map every **face** to a different $(n-1)$ -simplex.
- Every **simplex** is uniquely determined by its vertex set.
- Any $(n+1)$ vertices in X^0 is the vertex set of at most 1 n -simplex.

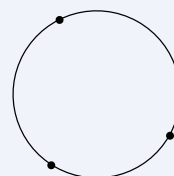
Example (Difference between simplicial and Δ -complex structure of S^1). With **Definition 5.2.7** and **Definition 5.2.8**, we see the followings.



Δ -simplex
not simplicial

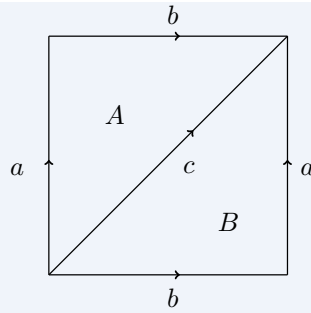


Δ -simplex
not simplicial



Δ -simplex
is simplicial

Example (Difference between simplicial and Δ -complex structure of a torus). The torus with the following edges, a, b, c and the gluing in triangles A and B can be seen as follows.



This structure is only valid as a Δ -complex.

Proof. For this Δ -complex, notice that we've glued down a triangle whose vertices are all identified. This is not allowed in a simplicial complex/triangulation.

Remark. The minimum number of triangles in a simplicial complex structure is 14.

Exercise. Try to come up with the corresponding simplicial complex.

⊛

Lecture 21: Simplicial Homology

To demonstrate how the definition of homology arise, we first see the idea behind it. Fix a space X which equips with the Δ -complex structure. Then, we define $C_n(X)$ to be the free Abelian group on the n -simplices of X . That is,

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$$C_n(X) = \left\{ \text{finite sums } \sum m_\alpha \sigma_\alpha \mid m_\alpha \in \mathbb{Z}, \sigma_\alpha: \Delta^n \rightarrow X \right\}.$$

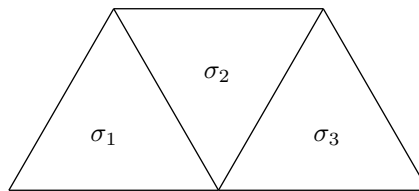
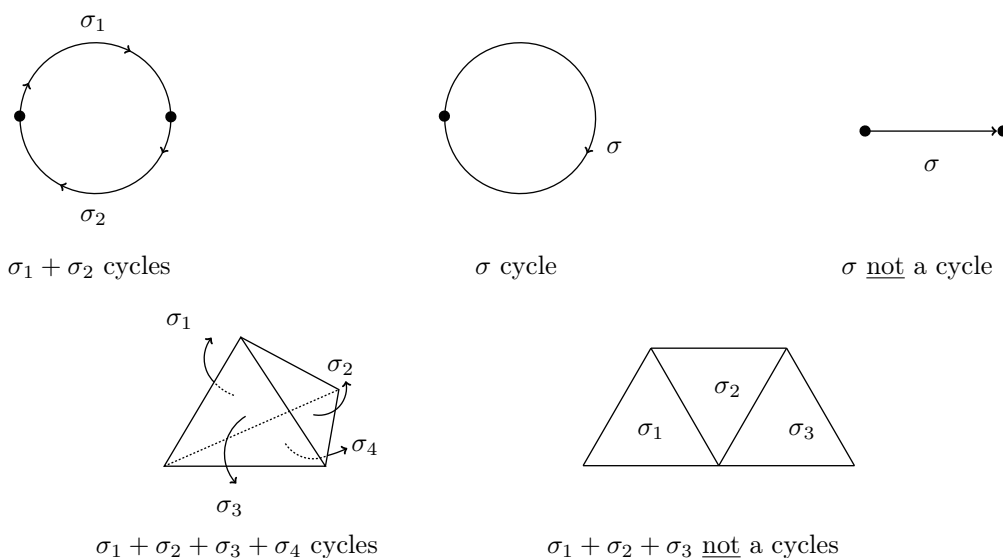


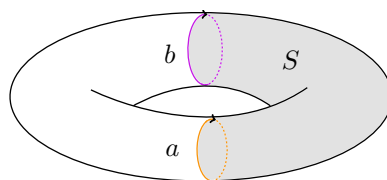
Figure 5.1: $C_2(X) = \mathbb{Z}\sigma_1 \oplus \mathbb{Z}\sigma_2 \oplus \mathbb{Z}\sigma_3$.

Then, the n -th homology group will be a subquotient of $C_n(X)$, where the heuristic/imprecise idea is

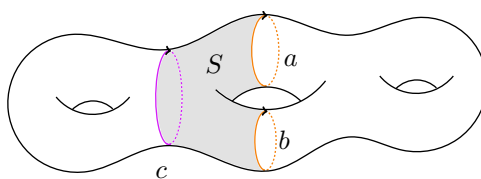
- Take subgroup of C_n of *cycles*. These are sums of simplices satisfying a combinatorial condition on the boundary gluing maps to ensure that they *close up*, i.e., they have no boundary.



- To take the **quotient**, we consider two cycles to be equivalent if their difference is a **boundary**. For example, in the case of torus, a is homologous to b since $a - b$ is the **boundary** of the shaded subsurface S on of the torus below.



In fact, a and b are **homotopic** (which will imply they're homologous essentially), but two loops do not need to be **homotopic** to be homologous. For example, in the figure below, $a + b$ is homologous to c , since $a + b - c$ is the **boundary** of S ($a + b$ ¹ and c are **not homotopic**).



Let's now see the formal definition.

Definition 5.2.9 (Simplicial chain group). We define the *simplicial chain group* $C_n(X)$ of order n to be the **free Abelian group** on the n -**simplices** of X such that

$$C_n(X) := \left\{ \text{finite sums } \sum m_\alpha \sigma_\alpha \mid m_\alpha \in \mathbb{Z}, \sigma_\alpha: \Delta^n \rightarrow X \right\}.$$

Definition 5.2.10 (Cycle). Given any chain group $C_n(X)$, a *cycle* of $C_n(X)$ is those chains $\sum m_\alpha \sigma_\alpha$ with no **boundaries**.

¹Which isn't even a loop

Definition 5.2.11 (Boundary homomorphism). A map $\partial_n: C_n(X) \rightarrow C_{n-1}(X)$ is called a *boundary homomorphism* such that

$$\begin{aligned} \partial_n: C_n(X) &\rightarrow C_{n-1}(X) \\ [\sigma_\alpha] &\mapsto \sum_{i=1}^n (-1)^i \sigma_\alpha|_{[v_0, \dots, \hat{v}_i, \dots, v_n]}, \end{aligned}$$

which defines the map on the basis, and we extend it linearly.

Remark. We see that the definition of [boundary homomorphism](#) indeed coincides with the definition of [boundary](#) when considering either [Δ-complex](#) or [simplicial complex](#) structure.

Example. We give some lower dimensions examples of [Definition 5.2.11](#) to motivate the general definition.

- For $n = 1$, $\partial_1: C_1(X) \rightarrow C_0(X)$ such that

$$[\sigma_\alpha: [v_0, v_1] \rightarrow X] \mapsto \sigma_\alpha|_{[v_1]} - \sigma_\alpha|_{[v_0]}.$$

- For $n = 2$, $\partial_2: C_2(X) \rightarrow C_1(X)$ such that

$$[\sigma_\alpha: [v_0, v_1, v_2] \rightarrow X] \mapsto \sigma_\alpha|_{[v_1, v_2]} - \sigma_\alpha|_{[v_0, v_2]} + \sigma_\alpha|_{[v_0, v_1]}.$$

Lemma 5.2.1. Let C_n being the [simplicial chain group](#) and ∂_n being the [boundary homomorphism](#), for any $n \geq 2$, we have

$$\begin{array}{ccccc} C_n(X) & \xrightarrow{\partial_n} & C_{n-1}(X) & \xrightarrow{\partial_{n-1}} & C_{n-2}(X) \\ & \searrow \partial_{n-1} \circ \partial_n = 0 & & & \end{array}$$

Proof. Since all C_i are [free Abelian group](#), hence we only need to consider $\partial_{n-1} \circ \partial_n(\sigma) = 0$ for a generator σ . Given a generator σ , the result follows from directly applying the [definition](#) and with some calculation. ■

Definition 5.2.12 (Chain complex). A *chain complex* (C_*, d_*) is a collection of maps d_n between groups C_n such that

$$\dots \longrightarrow C_{n+1} \xrightarrow{d_{n+1}} C_n \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \dots$$

of [Abelian groups](#) C_n and group homomorphism d_n such that

$$d_{n-1} \circ d_n = 0.$$

Additionally, we have the followings.

Definition 5.2.13 (Chain group). We call C_n the *n-th chain group*.

Definition 5.2.14 (Differential). We call d_n the *n-th differential*.

We see that we can certainly think C_n and d_n as the [simplicial chain group](#) and the [boundary homomorphism](#) as defined before since we already showed this combination satisfies [Definition 5.2.12](#) in [Lemma 5.2.1](#). But we note that the definition of C_n and d_n can be further abstract as what we have defined.

Note. As just discussed, we can put different **chain group** structure on C_n . We'll see what this means later.^a But for now, we think C_n be equipped with the definition we gave for **simplicial chain group**.

^aSpoiler: It just means we can give different definition about the map σ .

Remark. We see that

- **Lemma 5.2.1** guarantees that our **simplicial chain groups** form a **chain complex**.
- **Definition 5.2.12** means that $\ker(d_n)$ contains $\text{Im}(d_{n+1})$, since $d_n \circ d_{n+1} = 0$.

Definition 5.2.15 (Exact). We say that the sequence is *exact at C_n* provided that $\ker(d_n) = \text{Im}(d_{n+1})$. A **chain complex** is *exact* if it is *exact at each point*.

Definition 5.2.16 (Homology group). The n^{th} *homology group of a chain complex (C_*, d_*)* , denoted as H_n or $H_n(C_*)$, is the quotient

$$H_n := \ker(d_n) / \text{Im}(d_{n+1}).$$

Remark. The **homology group** measures how far the **chain complex** is from being **exact** at C_n .

With what we have just defined, it's natural to define **homology groups** of space X with a **Δ -complex** structure.

Definition 5.2.17 (Homology class). We say $\ker(\partial_n)$ is the subgroup of **cycles** in $C_n(X)$, and $\text{Im}(\partial_{n+1})$ is the subgroup of **boundaries** in $C_n(X)$. We then set

$$H_n(X) := \ker(\partial_n) / \text{Im}(\partial_{n+1}) = \{\text{cycles}\} / \{\text{boundaries}\}.$$

In other words, it's the **homology** of the **chain complex**

$$\dots \longrightarrow C_{n+1} \xrightarrow{\partial_{n+1}} C_n \xrightarrow{\partial_n} C_{n-1} \xrightarrow{\partial_{n-1}} \dots$$

where we take it to be 0 in all negative indices, namely

$$\dots \xrightarrow{\partial_3} C_{n+1} \xrightarrow{\partial_2} C_n \xrightarrow{\partial_1} C_{n-1} \xrightarrow{\partial_0} 0$$

We then call the elements of $H_n(X)$ as *homology classes*.

Remark. **Definition 5.2.17** is saying that we should call the element of a **homology group** whose **chain group** is some kinds of **geometric subjects**. In this case, we're just considering **Δ -complex** structure, but the definition of **homology class** is in fact more general.

Definition 5.2.18 (Simplicial homology group). By considering the **chain complex** being the **simplicial chain groups** and **boundary homomorphisms**, we have so-called *simplicial homology groups* induced by **Definition 5.2.16**.

Lecture 22: Calculation of Homology

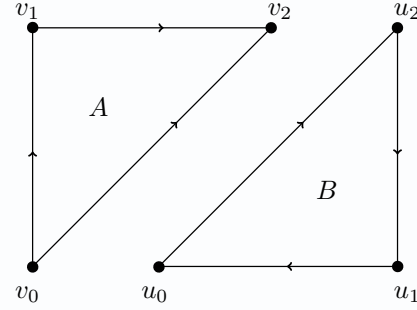
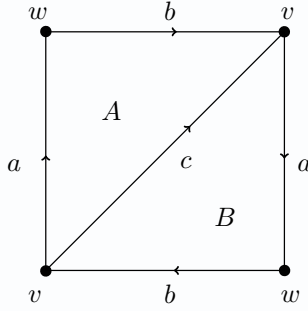
5.2.2 Calculation of Homology

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We start from some calculation about **homology group** of some spaces.

Example (Homology group of $\mathbb{R}P^2$). Calculate the homology group by Definition 5.2.16 with the chain complex being the simplicial chain complex.

Proof. Let $X = \mathbb{R}P^2$.



We see that we have

- $C_0 = \mathbb{Z}\langle v, w \rangle$
- $C_1 = \mathbb{Z}\langle a, b, c \rangle$
- $C_2 = \mathbb{Z}\langle A, B \rangle = \mathbb{Z}A \oplus \mathbb{Z}B$

The chain complex is then

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

Where we let $A = [v_0, v_1, v_2]$ and $B = [u_0, u_1, u_2]$, then

$$\partial_2: \begin{cases} A \mapsto b - c + a \\ B \mapsto -a - c - b \end{cases}, \quad \partial_1: \begin{cases} a \mapsto w - v \\ b \mapsto v - w \\ c \mapsto v - v = 0 \end{cases}$$

We can also calculate the image and the kernel at C_i , i.e.,

$$\begin{aligned} C_2: \operatorname{Im} \partial_3 &= 0, & \ker \partial_2 &= 0, \\ C_1: \operatorname{Im} \partial_2 &= \langle 2c, b - c + a \rangle, & \ker \partial_1 &= \langle b + a, c \rangle, \\ C_0: \operatorname{Im} \partial_1 &= \langle v - w \rangle, & \ker \partial_0 &= \langle v, w \rangle. \end{aligned}$$

Hence,

$$\begin{aligned} H_0 &\cong \mathbb{Z}\langle v, w \rangle / \mathbb{Z}\langle v - w \rangle \cong \mathbb{Z} \\ H_1 &\cong \mathbb{Z}\langle b + a, c \rangle / \mathbb{Z}\langle 2c, b + a - c \rangle \cong \mathbb{Z}\langle b + a - c, c \rangle / \mathbb{Z}\langle 2c, b + a - c \rangle \cong \mathbb{Z} / 2\mathbb{Z} \\ H_2 &= 0 \end{aligned}$$

⊗

Remark. Given a basis for a free Abelian group $\langle b_1, \dots, b_n \rangle$ we can replace b_i with

$$b_i \pm m_1 b_1 \pm \dots \pm \widehat{m_i b_i} \pm \dots \pm m_n b_n.$$

Remark. Care is needed when doing *change of bases* over \mathbb{Z} . For example, if b_1, b_2 is a basis for $A \subseteq \mathbb{Z}^n$, then $b_1 - b_2, b_1 + b_2$ is **not** a basis, it is an index-2 subgroup. The key to this is that

$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ has determinant -2 (**not** unit in \mathbb{Z}).

We can transform a basis for a **free group** into a different basis by applying a matrix of determinant ± 1 . If we apply a matrix of determinant D we will obtain generators for a subgroup of index $|D|$.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & \pm m_1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \pm m_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \pm m_{i-1} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & \pm m_{i+1} & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & \pm m_n & 0 & \cdots & 1 \end{bmatrix}$$

As a summary, we have the following procedures to compute $H_n(X)$.

- (1) Choose **Δ -complex** structure on X . (We will prove $H_*(X)$ is independent of the choice of **Δ -complex** structure)
- (2) Choose orientations on each **simplex** (Any choice is okay, but you must commit to a choice, or you will make a sign error!)
- (3) For each **n -simplex** σ compute $\partial_n(\sigma)$ (careful with signs!)
- (4) $\text{Im } \partial_n = \langle \partial_n(\sigma) \mid \sigma \text{ an } n\text{-simplex} \rangle$. Use linear algebra to compute $\ker(\partial_n)$.
- (5) For each n compute $H_n(X) = \ker \partial_n / \text{Im } \partial_{n+1}$. Be careful that any change-of-variables map you apply is invertible over \mathbb{Z} .

Lecture 23: Singular Homology

5.3 Singular Homology

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As we noted before, we can give a different structure of **chain complex**, which shall induce a different **homology group** compare to **simplicial homology group**.

We now see one abstract way to define σ , which will give us so-called **singular homology group**.

Definition 5.3.1 (Singular simplex). A *singular n -simplex* in a space X is a continuous map

$$\sigma: \Delta^n \rightarrow X.$$

Definition 5.3.2 (Singular chain complex). The **chain complex** defined with **singular chain group** and **singular boundary map** defined as follows is called *singular chain complex*.

Definition 5.3.3 (Singular chain group). Let $C_n(X)$ be the **free group** on **singular n -simplices** in X , which we call it the *singular n -chain group*.

Definition 5.3.4 (Singular boundary map). With C_* being the **singular chain group**, we defined so-called *singular boundary map* ∂_n as

$$\begin{aligned} \partial_n: C_n(X) &\rightarrow C_{n-1}(X) \\ \sigma &\mapsto \sum_{i=1}^n (-1)^i \sigma|_{[v_0, \dots, \widehat{v_i}, \dots, v_n]}. \end{aligned}$$

Definition 5.3.5 (Singular homology group). The *singular homology groups* are the [homology groups](#) of this [singular chain complex](#) given as

$$H_n(X) = \ker \partial_n / \operatorname{Im} \partial_{n+1}.$$

Remark. We now see that from the definition of [homology group](#), we can put different structure on which. But the idea is the same, namely we are taking $H_n(X)$ being

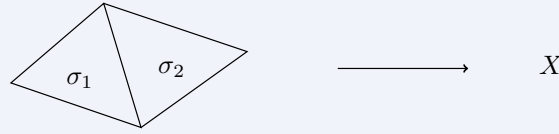
$$H_n(X) := \ker \partial_n / \operatorname{Im} \partial_{n+1},$$

where the difference is what structure we put on X which induces different [chain complex](#) $(C_*(X), \partial_*)$. In this case, we have [singular homology group](#) since we are considering [singular chain complex](#), while we can also have [simplicial homology group](#).

Since the generating sets for $C_n(X)$ when considering [singular chain complex](#) are almost always hugely uncountable from its definition, it's almost impossible to compute with these. However, it does give us a definition that does not depend on any other structure than the topology of X , making it useful for developing theory.

Note. The heuristic is that, we interpret a [chain](#) $\sigma_1 \pm \sigma_2 \pm \cdots \pm \sigma_k$ as a map from a [\$\Delta\$ -complex](#) to X .

Example. For example, with $\sigma_1 + \sigma_2$ as below,



where we've glued $[v_1, v_2]$ of σ_1 to $[v_0, v_2]$ of σ_2 if $\sigma_1|_{[v_1, v_2]}$ and $\sigma_2|_{[v_0, v_2]}$ are the same [singular \$n\$ -chain](#) with opposite signs.

With what we have defined, we now have some *goals*.

- [Singular homology](#) is a [homotopy](#) invariant. ([Theorem 5.4.2](#))
- [Singular](#) and [simplicial homology groups](#) are isomorphic. ([Theorem 5.5.6](#))

Exercise. Check that if X has [path](#) components $\{X_\alpha\}$ then

$$H_n(X) \cong \bigoplus_{\alpha} H_n(X_\alpha).$$

Exercise. If $X = \{*\}$, then

$$H_n(X) = \begin{cases} \mathbb{Z}, & \text{if } n = 0; \\ 0, & \text{if } n \geq 1. \end{cases}$$

Exercise. If X is [path](#)-connected, then $H_0(X) \cong \mathbb{Z}$.

5.4 Functoriality and Homotopy Invariance

Definition 5.4.1 (Induced map on singular chains). For a given continuous map $f: X \rightarrow Y$, we can consider the map $f_\#$ induced by [singular chains](#) as

$$\begin{aligned} f_\# : C_n(X) &\rightarrow C_n(Y) \\ [\sigma : \Delta^n \rightarrow X] &\mapsto [f \circ \sigma : \Delta^n \rightarrow Y]. \end{aligned}$$

Note. Note that we're considering [singular chain groups](#) specifically in this case.

Remark. We see that the functoriality doesn't depend on any kind of [Δ-complex](#) structure.

Definition 5.4.2 (Chain map). Given two [chain complexes](#) (C_*, ∂_*) and (D_*, δ_*) , a *chain map* between them is a collection of group homomorphisms $f_n : C_n \rightarrow D_n$ such that the following diagram commutes.

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

i.e. we have that $\delta_n \circ f_n = f_{n-1} \circ \partial_n$.

Exercise. We have that $f_\# \partial = \partial f_\#$. In other words, $f_\#$ is a [chain map](#). Thus, by the homework $f_\#$ induces a group homomorphism on the [homology groups](#). We write this as $f_* : H_n(X) \rightarrow H_n(Y)$ for all n .

Exercise. We have functoriality, i.e. $(f \circ g)_* = f_* \circ g_*$ and $(\text{id}_X)_* = \text{id}_{H_n(X)}$.

Theorem 5.4.1 (Homology group defines a functor). The n -th [homology group](#) $H_n : X \mapsto H_n(X)$ gives a [functor](#) from [Top](#) to [Ab](#).

Proof. This follows from the two exercises above. ■

Theorem 5.4.2 (Functoriality is homotopy invariant). If $f, g : X \rightarrow Y$ are [homotopic](#), then they will induce the same map on [homology](#)

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

The proof of [Theorem 5.4.2](#) can be found [here](#).

Exercise. [Theorem 5.4.1](#) and [Theorem 5.4.2](#) imply that H_n is a [homotopy](#) invariant.

I'm not sure whether the above discussion holds only for [singular homology group](#) or can be extended to [general homology group](#). I link them to [general homology group](#) anyway.

Lecture 24: Chain Homotopy

To prove [Theorem 5.4.2](#), we introduce some [homological algebra](#).

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Definition 5.4.3 (Chain homotopy). Given [chain complexes](#) (A_*, ∂_*^A) and (B_*, ∂_*^B) and [chain maps](#) $f_\#, g_\# : A_* \rightarrow B_*$. A *chain homotopy* from $f_\#$ to $g_\#$ is a sequence of group homomorphisms $\psi_n : A_n \rightarrow B_{n+1}$ such that

$$f_n - g_n = \partial_{n+1}^B \circ \psi_n + \psi_{n-1} \circ \partial_n^A.$$

In diagram, letting $h_n := f_n - g_n$, we have the following.

$$\begin{array}{ccccccc}
 \dots & \xrightarrow{\partial_{n+2}^A} & A_{n+1} & \xrightarrow{\partial_{n+1}^A} & A_n & \xrightarrow{\partial_n^A} & A_{n-1} \xrightarrow{\partial_{n-1}^A} \dots \\
 & & \downarrow h_{n+1} & \swarrow \psi_n & \downarrow h_n & \swarrow \psi_{n-1} & \downarrow h_{n-1} \\
 \dots & \xrightarrow{\partial_{n+2}^B} & B_{n+1} & \xrightarrow{\partial_{n+1}^B} & B_n & \xrightarrow{\partial_n^B} & B_{n-1} \xrightarrow{\partial_{n-1}^B} \dots
 \end{array}$$

This diagram does **not** commute, however, the **red** map is the sum of the **blue** maps composed up, so it shows everything that is going on.

Theorem 5.4.3. If there is a **chain homotopy** ψ from $f_\#$ to $g_\#$, then the induced maps f_*, g_* on **homology** are equal.

Proof. Let $\sigma \in A_n$ be an n -cycle, i.e. $\partial_n^A \sigma = 0$. Then we compute that:

$$(f_n - g_n)(\sigma) = \partial_{n+1}^B(\psi_n(\sigma)) + \psi_{n-1}(\partial_n^A(\sigma)) = \partial_{n+1}^B(\psi_n(\sigma)) \in \text{Im}(\partial_{n+1}^B).$$

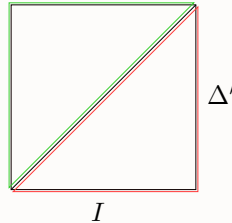
This tells us that $(f_n - g_n)(\sigma)$ is a **boundary**, and so $(f_n - g_n)(\sigma) = 0$ when considered as an element of the **homology group** (with degree n). Thus, $f_n(\sigma) = g_n(\sigma)$ in the **homology group**, and so f, g induce the same map as desired. ■

We now sketch the proof of **Theorem 5.4.2** given in Hatcher[HPM02]. From this point in the course many of the theorems require much more algebraic work than we are interested in. We instead want to learn how to use the computational tools.

Proof sketch of Theorem 5.4.2. Suppose we have some **homotopy** $F: I \times X \rightarrow Y$ from f to g . The most difficulty in this proof is the combinatorial difficulty involved in the fact that the product of a **simplex** in X and I is not a **simplex**.

We now consider

- (1) Subdivide $\Delta^n \times I$ into $(n+1)$ -dimensional **subsimplces**.^a



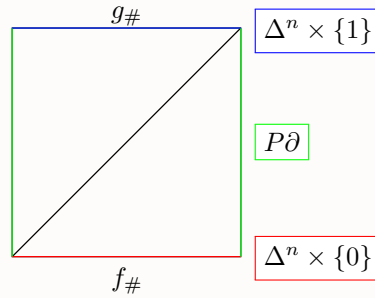
- (2) We define the **prism** operator:

$$\begin{aligned}
 P_n: C_n(X) &\rightarrow C_{n+1}(Y) \\
 [\sigma: \Delta^n \rightarrow X] &\mapsto \left[\begin{array}{l} \text{alternating sums of restrictions} \\ \Delta^n \times I \xrightarrow{\sigma \times \text{id}} X \times I \xrightarrow{F} Y \\ \text{to each simplex in our subdivision} \end{array} \right]
 \end{aligned}$$

- (3) We now need to check that

$$\partial_{n+1}^Y P_n = \boxed{g_\#} - \boxed{f_\#} - \boxed{P_{n-1} \partial_n^X}.$$

We have the following diagram.



Thus P is a [chain homotopy](#), and we're done. ■

^aWe want to do this since the product between two [simplices](#) is not a [simplex](#), as we just note.

Lecture 25: Relative Homology

We are now interested in the relationship between $H_n(X), H_n(A), H_n(X/A)$.

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5.5 Relative Homology

Definition 5.5.1 (Reduced homology group). The *reduced homology groups* $\tilde{H}_n(X) = H_n(X)$ when $n > 0$. When $n = 0$ we have that:

$$\tilde{H}_0(X) \oplus \mathbb{Z} = H_0(X).$$

Remark. The usefulness of this is that for [path-connected](#) space X we have $\tilde{H}_0(X) = 0$, and for [contractible](#) spaces X we have $\tilde{H}_n(X) = 0$.

Definition 5.5.2 (Good pair). Let X be a space, and $A \subseteq X$. Then (X, A) is a *good pair* if A is closed and nonempty, and also it is a [deformation retract](#) of a neighborhood in X .

Example. Let's see some examples.

- (1) If X is a [CW complex](#) and A is a nonempty [subcomplex](#), then (X, A) is a [good pair](#). The proof is given in the Appendix of Hatcher[HPM02] and requires some point-set topology.
- (2) If M is a smooth manifold, and $N \subseteq M$ is a smooth submanifold which is nonempty, then (M, N) is a [good pair](#).
- (3) (Hawaiian earring, bad point) is **not** a [good pair](#).
- (4) $(\mathbb{R}^n, \text{proper open set})$ is **not** a [good pair](#).

Theorem 5.5.1 (Long exact sequence of a good pair). If (X, A) is a [good pair](#), then there exists a long [exact sequence](#) ([exact](#) at every n) on [reduced homology groups](#) given by the following commutative

diagram.

$$\begin{array}{ccccccc}
 \dots & \longrightarrow & \tilde{H}_n(A) & \xrightarrow{i_*} & \tilde{H}_n(X) & \xrightarrow{j_*} & \tilde{H}_n(X/A) \\
 & & & & \searrow \delta & & \\
 & & \tilde{H}_{n-1}(A) & \xrightarrow{i_*} & \tilde{H}_{n-1}(X) & \xrightarrow{j_*} & \tilde{H}_{n-1}(X/A) \\
 & & & & \searrow \delta & & \\
 & & \dots & \xleftarrow{i_*} & \tilde{H}_0(X) & \xrightarrow{j_*} & \tilde{H}_0(X/A) \longrightarrow 0
 \end{array}$$

where $i: A \hookrightarrow X$ is the inclusion and $j: X \rightarrow X/A$ is the quotient map.

We see that both i_* and j_* is naturally induced, but not for δ . In fact, we'll construct δ in the proof! Specifically, we'll see that [Theorem 5.5.1](#) is just a special case of [Theorem 5.5.3](#), hence rather than proving [Theorem 5.5.1](#) directly, we will prove [Theorem 5.5.3](#) instead later.

Remark. The fact that this sequence is [exact](#) often means that if we know the [homology groups](#) of two of the spaces we can compute the [homology](#) of the remaining space.

Before we see the proof of [Theorem 5.5.1](#), we see one application.

Proposition 5.5.1. We have that

$$\tilde{H}_i(S^n) = \begin{cases} \mathbb{Z}, & \text{if } i = n; \\ 0, & \text{if } i \neq n. \end{cases}$$

Proof. Some facts we need:

- $(D^n, \partial D^n)$ is a [good pair](#) (since it is a [CW complex](#) and a [subcomplex](#))
- $D^n / \partial D^n \cong S^n$.
- $\tilde{H}_n(D^n) = 0$ for all n since D^n is [contractible](#).
- $\partial D^n \cong S^{n-1}$.

We then proceed by induction on n . To start with, we need to verify the following.

Exercise. Verify [Proposition 5.5.1](#) in the case $n = 0$, so S^0 is just 2 points.

Now, using the long [exact sequence](#), we have

$$\begin{array}{ccccccc}
 \dots & \longrightarrow & \tilde{H}_n(\partial D^n) & \xrightarrow{i_*} & \tilde{H}_n(D^n) & \xrightarrow{j_*} & \tilde{H}_n(S^n) \\
 & & & & \searrow \delta & & \\
 & & \tilde{H}_{n-1}(\partial D^n) & \xrightarrow{i_*} & \tilde{H}_{n-1}(D^n) & \xrightarrow{j_*} & \tilde{H}_{n-1}(S^n) \\
 & & & & \searrow \delta & & \\
 & & \dots & \xleftarrow{i_*} & \tilde{H}_0(D^n) & \xrightarrow{j_*} & \tilde{H}_0(S^n) \longrightarrow 0
 \end{array}$$

By induction, we have $\tilde{H}_{n-1}(\partial D^n) = \tilde{H}_{n-1}(S^{n-1}) = \mathbb{Z}$, hence we can fill in some of these groups as follows.

$$\begin{array}{ccccccc}
 \dots & \longrightarrow & 0 & \xrightarrow{i_*} & 0 & \xrightarrow{j_*} & \tilde{H}_n(S^n) \\
 & & & & \searrow \delta & & \\
 & & \mathbb{Z} & \xleftarrow{i_*} & 0 & \xrightarrow{j_*} & \tilde{H}_{n-1}(S^n) \\
 & & & & \searrow \delta & & \\
 & & \dots & \xleftarrow{i_*} & 0 & \xrightarrow{j_*} & \tilde{H}_0(S^n) \longrightarrow 0
 \end{array}$$

In all, we have an [exact sequence](#)

$$0 \longrightarrow \tilde{H}_n(S^n) \xrightarrow{\delta} \mathbb{Z} \longrightarrow 0$$

By [exactness](#), δ is an isomorphism, thus $\tilde{H}_n(S^n) \cong \mathbb{Z}$. Now we must verify $\tilde{H}_i(S^n) = 0$ when $i \neq n$. In that case the [exact sequence](#) looks like:

$$\begin{array}{ccccccc} \longrightarrow & \tilde{H}_i(D^n) & \longrightarrow & \tilde{H}_i(S^n) & \longrightarrow & \tilde{H}_{i-1}(\partial D^n) & \\ & \longrightarrow & 0 & \longrightarrow & \tilde{H}_i(S^n) & \longrightarrow & 0 \end{array}$$

[Exactness](#) then tells us that $\tilde{H}_i(S^n) = 0$. ■

Theorem 5.5.2 (Brouwer's fixed point theorem). ∂D^n is not a [retract](#) of D^n . Hence, every continuous map $f: D^n \rightarrow D^n$ has a fixed point.

Proof. If $r: D^n \rightarrow \partial D^n$ were a [retraction](#), then by definition this would give us

$$\begin{array}{ccccc} \partial D^n & \xrightarrow{i} & D^n & \xrightarrow{r} & \partial D^n \\ & & \searrow \text{id}_{\partial D^n} & & \nearrow \end{array}$$

[Functoriality](#) of [homology](#) implies

$$\begin{array}{ccccc} \tilde{H}_{n-1}(\partial D^n) & \xrightarrow{i_*} & \tilde{H}_{n-1}(D^n) & \xrightarrow{r_*} & \tilde{H}_{n-1}(\partial D^n) \\ & & \searrow \text{id} & & \nearrow \end{array}$$

So then:

$$\begin{array}{ccccc} \mathbb{Z} & \xrightarrow{i_*} & 0 & \xrightarrow{r_*} & \mathbb{Z} \\ & & \searrow \text{id} & & \nearrow \end{array}$$

which is impossible since the map $\text{id}_{\mathbb{Z}}$ can't be factored through 0. ■

Exercise. As with D^2 , if $f: D^n \rightarrow D^n$ had no fixed point, we could build a [retraction](#).

In order to proof [Theorem 5.5.1](#), we introduce the concept of *diagram chase*.

Lemma 5.5.1 (The short five lemma). Suppose we have a commutative diagram

$$\begin{array}{ccccccccc} 0 & \longrightarrow & A & \xrightarrow{\psi} & B & \xrightarrow{\varphi} & C & \longrightarrow & 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma & & \\ 0 & \longrightarrow & A' & \xrightarrow{\psi'} & B & \xrightarrow{\varphi'} & C' & \longrightarrow & 0 \end{array}$$

so that the rows are [exact](#). Then:

- (1) If α, γ are injective then β is injective.
- (2) If α, γ are surjective then β is surjective.
- (3) If α, γ are isomorphisms then β is an isomorphism

Proof. (1) and (2) imply (3) We leave (2) as an exercise. We fix $b \in B$ such that $\beta(b) = 0$. We

want to show that $\beta = 0$, which can be done by doing a *diagram chase* as

$$\begin{array}{ccccccc} 0 & \longrightarrow & \bullet & \xrightarrow{\psi} & b & \xrightarrow{\varphi} & \varphi(b) \longrightarrow 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma \\ 0 & \longrightarrow & \bullet & \xrightarrow{\psi'} & 0 & \xrightarrow{\varphi'} & 0 \longrightarrow 0 \end{array}$$

And thus by injectivity of γ we know $\varphi(b) = 0$. By [exactness](#), $b \in \text{Im } \psi$. We then may write for some $a \in A$ such that the following diagram commutes.

$$\begin{array}{ccccccc} 0 & \longrightarrow & a & \xrightarrow{\psi} & b & \xrightarrow{\varphi} & 0 \longrightarrow 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma \\ 0 & \longrightarrow & \alpha(a) & \xrightarrow{\psi'} & 0 & \xrightarrow{\varphi'} & 0 \longrightarrow 0 \end{array}$$

Therefore $\psi'(\alpha(a)) = \beta(\psi(a)) = \beta(b) = 0$ by commutativity. By [exactness](#) of the bottom row we know that ψ' is an injection.

Thus, $\alpha(a) = 0$, so since α is injective, $a = 0$. With this $b = \psi(a) = \psi(0) = 0$. With this, $\ker(\beta) = 0$, and β injects. ■

Lecture 26: Continue on Relative Homology

We start from a definition.

14 Mar. 10:00

Definition 5.5.3 (Relative chain group). Let X be a space and let $A \subseteq X$ be a subspace. Then we define the *relative chain group* as

$$C_n(X, A) = C_n(X) / C_n(A),$$

which is a quotient of [Abelian groups](#) of the [singular chain groups](#) between X and A .

Definition 5.5.4 (Relative chain complex). The *relative chain complex* (C_*, ∂_*) consists of [relative chain group](#) and the usual [differential](#) associated with the [singular chain groups](#) which induces our [relative chain group](#).

Remark. We can indeed adapt [Definition 5.5.4](#) by either [singular chain complex](#) structure or [simplicial chain complex](#) structure.

It's not entirely clear that whether [Definition 5.5.4](#) is well-defined, hence we have the following exercise.

Exercise. Since $\partial_n^*(C_n(A)) \subseteq C_{n-1}(A)$, hence there exists a well-defined map

$$\partial_n: C_n(X) / C_n(A) \rightarrow C_{n-1}(X) / C_{n-1}(A).$$

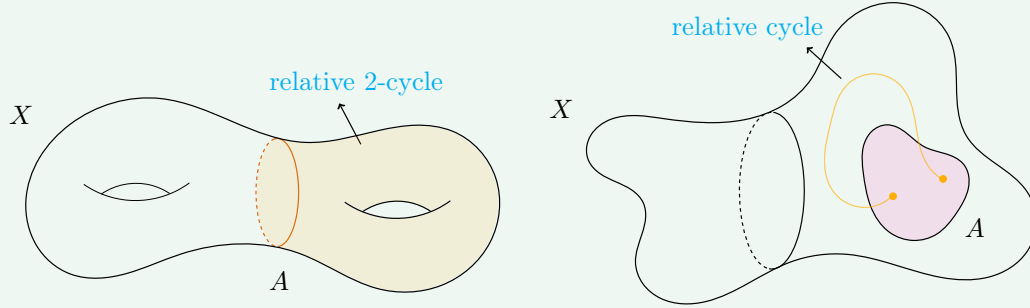
We can verify that $\partial^2 = 0$. Then, since $\partial^2 = 0$ we can conclude that these groups will in fact form a [chain complex](#) $(C_*(X, A), \partial)$.

Definition 5.5.5 (Relative homology group). The [homology groups](#) of the [relative chain complex](#) $(C_*(X, A), \partial)$ are denoted by $H_n(X, A)$, and they are called *relative homology groups*.

We see that there are something interesting going on in [relative chain group](#). Indeed, we can further classify the [cycles](#) in which as follows.

Definition. Let $C_*(X)$ be the [relative chain complex](#).

Definition 5.5.6 (Relative cycle). Elements in $\ker \partial_n$ are called *relative n -cycles*. These are elements $\alpha \in C_n(X)$ such that $\partial_n \alpha \in C_{n-1}(A)$.



Definition 5.5.7 (Relative boundary). Elements α in $\text{Im } \partial_{n+1}$ are called *relative n -boundaries*. This means that $\alpha = \partial \beta + \gamma$ where $\beta \in C_n(X)$ and $\gamma \in C_{n-1}(A)$.

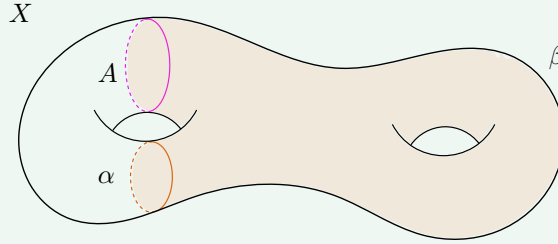


Figure 5.2: We see that we have $\alpha + \gamma = \partial \beta$, where α is a [relative boundary](#), and $\gamma \in C_{n-1}(A)$.

Theorem 5.5.3 (Long exact sequence of a pair). Let $A \subseteq X$ be spaces, then there exists a long [exact sequence](#)

$$\begin{array}{ccccccc} \dots & \longrightarrow & \tilde{H}_n(A) & \xrightarrow{i_*} & \tilde{H}_n(X) & \xrightarrow{q} & \tilde{H}_n(X, A) \\ & & & & \searrow \partial & & \\ & & \tilde{H}_{n-1}(A) & \xleftarrow{i_*} & \dots & \xrightarrow{q} & \tilde{H}_0(X, A) \longrightarrow 0 \end{array}$$

where i_* is induced by $A \hookrightarrow X$, and q is induced by $C_n(X) \twoheadrightarrow C_n(X) / C_n(A)$.

We will prove that when (X, A) is a [good pair](#), then $H_n(X, A) \cong \tilde{H}_n(X / A)$. Then [Theorem 5.5.1](#) is a special case of [Theorem 5.5.3](#). The key to the proof of [Theorem 5.5.3](#) above is the following remark.

Remark. A [short exact sequence of chain complexes](#) gives rise to a long [exact sequence of homology groups](#). Namely, given a [short exact sequence of chain complexes](#) $(A_*, \partial^A), (B_*, \partial^B), (C_*, \partial^C)$ such that

$$0 \longrightarrow A_* \xrightarrow{\iota} B_* \xrightarrow{q} C_* \longrightarrow 0$$

where ι, q are [chain maps](#) such that

$$0 \longrightarrow A_n \xrightarrow{\iota_n} B_n \xrightarrow{q_n} C_n \longrightarrow 0$$

is exact for all n . Then Theorem 5.5.1 will follow from a short exact sequence

$$0 \longrightarrow \tilde{C}_*(A) \longrightarrow \tilde{C}_*(X) \longrightarrow \tilde{C}_*(X, A) \longrightarrow 0$$

where \tilde{C}_* denotes the *augmented chain complex* (the one with \mathbb{Z} after it, as in Definition 5.5.1).

Exercise. If A is a single point in X , then $H_n(X, A) = \tilde{H}_n(X / A) = \tilde{H}_n(X)$.

Lecture 27: Excision

Let's start with a theorem.

16 Mar. 10:00

Theorem 5.5.4 (Excision). Suppose we have subspace $Z \subseteq A \subseteq X$ such that $\bar{Z} \subseteq \text{Int}(A)$. Then the inclusion

$$(X - Z, A - Z) \hookrightarrow (X, A)$$

induces isomorphisms

$$H_n(X - Z, A - Z) \xrightarrow{\cong} H_n(X, A).$$

Proof Sketch. We first see an equivalent formulation of Theorem 5.5.4.

Remark. Equivalently, for subspaces $A, B \subseteq X$ whose interiors cover X , the inclusion

$$(B, A \cap B) \hookrightarrow (X, A)$$

induces an isomorphism

$$H_n(B, A \cap B) \xrightarrow{\cong} H_n(X, A)$$

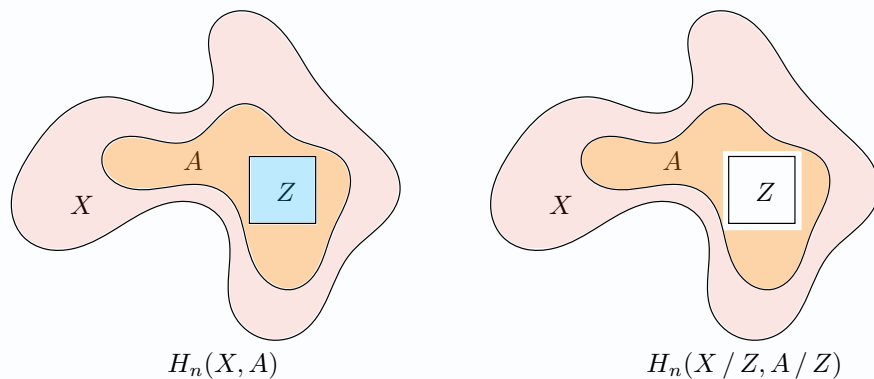
Proof. We see that this follows from

$$B := X \setminus Z, \quad Z = X \setminus B,$$

then we see that $A \cap B = A - Z$ and the condition requires from Theorem 5.5.4, $\bar{Z} \subseteq \text{Int}(A)$ is then equivalent to

$$X = \text{Int}(A) \cup \text{Int}(B)$$

since $X \setminus \text{Int}(B) = \bar{Z}$.



⊗

We now sketch the proof of the above equivalent form of Theorem 5.5.4, which is notorious for

being hairy.

- Given a **relative cycle** x in (X, A) , subdivide the **simplices** to make x a linear combination of chains on *smaller simplices*, each contained in $\text{Int}(A)$ or $X \setminus Z$.



Figure 5.3: $\Delta^n \rightarrow X$ subdivide into **subsimpllices** with images in.

This means x is homologous to sum of **subsimpllices** with images in $\text{Int}(A)$ or $X \setminus Z$. One of the things we use is that **simplices** are compact, so this process takes finite time.

The key is that the **Subdivision operator** is chain **homotopic** to the identity.

- Since we are working **relative** to A , the **chains** with image in A are zero, thus we have a **relative cycle** homologous to x with all **simplices** contained in $X \setminus Z$.

■

Exercise. Show that $H_*(Y, y_0) \cong \tilde{H}_*(Y)$.

Theorem 5.5.5. For **good pairs** (X, A) , the quotient map $q: (X, A) \rightarrow (X/A, A/A)$ induces isomorphisms

$$q_*: H_n(X, A) \xrightarrow{\cong} H_n(X/A, A/A) \cong \tilde{H}_n(X/A)$$

for all n .

Proof Sketch. Let $A \subseteq V \subseteq X$ where V is a neighborhood of A that **deformation retracts** onto A . Using **excision**, we obtain a commutative diagram

$$\begin{array}{ccccc} H_n(X, A) & \xrightarrow{\cong} & H_n(X, V) & \xleftarrow{\cong} & H_n(X - A, V - A) \\ \downarrow q_* & & \downarrow q_* & & \downarrow \cong q_* \\ H_n(X/A, A/A) & \xrightarrow{\cong} & H_n(X/A, V/A) & \xleftarrow{\cong} & H_n(X/A - A/A, V/A - A/A) \end{array}$$

Done if we can prove all the colored isomorphisms.

- \cong is an isomorphism by **excision**.
- \cong is an isomorphism by direct calculation (since q is a homeomorphism on the complement of A).
- \cong on Homework, since V **deformation retracts** to A .

Remark. The last equality is from the above exercise with $A/A = \{*\}$.

■

Lecture 28: Singular Homology v.s. Simplicial Homology

18 Mar. 10:00

Remark. If M is a smooth manifold and N is an embedded smooth closed submanifold, then (M, N) is a **good pair**. Why? Well this follows from the tubular neighborhood theorem, which should be proven in a course like MATH 591. We will only use the result in obvious cases, and simply assert that certain pairs are **good pairs**.

Example. With pairs like (\mathbb{R}^{n+1}, S^n) , you can just assert that this is a **good pair**.

Proof. If we want to be rigorous, we need to show that S^n is a smooth submanifold of \mathbb{R}^{n+1} , but we simply assert this in our course. \circledast

Example. Manifolds and their boundary always form a **good pair**.

Theorem 5.5.6 (Singular homology agrees with simplicial homology). Let X be a **Δ -complex**. We use $\Delta_n(X)$ to represent the **simplicial chain groups** on X , and $C_n(X)$ to denote the **singular chain groups**. Likewise, we denote

$$\Delta_n(X, A) = \Delta_n(X) / \Delta_n(A)$$

and

$$C_n(X, A) = C_n(X) / C_n(A).$$

The inclusion $\Delta_*(X, A) \hookrightarrow C_*(X, A)$ given by

$$[\sigma : \Delta^n \rightarrow X] \mapsto [\sigma : \Delta^n \rightarrow X]$$

induces an isomorphism on **homology** such that

$$H_n^\Delta(X, A) \cong H_n(X, A).$$

If we consider the case that $A = \emptyset$, we recover the case of **absolute homology**

$$H_n^\Delta(X) \cong H_n(X).$$

The proof of Theorem 5.5.6 uses the following lemma.

Lemma 5.5.2 (The five lemma). If we have a commutative diagram with **exact** rows as following,

$$\begin{array}{ccccccccc} A & \xrightarrow{i} & B & \xrightarrow{j} & C & \xrightarrow{k} & D & \xrightarrow{\ell} & E \\ \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma & & \downarrow \delta & & \downarrow \epsilon \\ A' & \xrightarrow{i'} & B' & \xrightarrow{j'} & C' & \xrightarrow{k'} & D' & \xrightarrow{\ell'} & E' \end{array}$$

If $\alpha, \beta, \delta, \epsilon$ are isomorphisms, then so is γ .

Proof. Diagram chase! ■

Lecture 29: Proof of Theorem 5.5.6

21 Mar. 10:00

We now give a proof sketch for Theorem 5.5.6.

Proof Sketch of Theorem 5.5.6. The idea is as follows.

- We can use the **long exact sequence of a pair** and the Lemma 5.5.2 to reduce to proving the result for **absolute homology groups** (and we will recover the general result).
- Because the image $\Delta^n \rightarrow X$ is **compact**, it is contained in some finite **skeleton** X^k . Use this

to reduce the proof to the finite **skeleton** X^k of X , namely we can use induction.

From the **long exact sequence of a pair** we get

$$\begin{array}{ccccccccc}
 H_{n+1}^\Delta(X^k, X^{k-1}) & \longrightarrow & H_n^\Delta(X^{k-1}) & \longrightarrow & H_n^\Delta(X^k) & \longrightarrow & H_n^\Delta(X^k, X^{k-1}) & \longrightarrow & H_{n-1}^\Delta(X^{k-1}) \\
 \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma & & \downarrow \delta & & \downarrow \epsilon \\
 H_{n+1}(X^k, X^{k-1}) & \longrightarrow & H_n(X^{k-1}) & \longrightarrow & H_n(X^k) & \longrightarrow & H_n(X^k, X^{k-1}) & \longrightarrow & H_{n-1}(X^{k-1})
 \end{array}$$

The Goal is to prove γ is an isomorphism using the **Lemma 5.5.2**.

We assume that β, ϵ are isomorphisms by induction, checking the case manually for X^0 (which will be a discrete set of points).

Exercise. Check the base case, namely when X^0 .

It remains to show that α, δ are isomorphisms. We know then that

$$\Delta_n(X^k, X^{k-1}) = \begin{cases} \mathbb{Z}[\textit{k-simplices}], & \text{if } k = n; \\ 0, & \text{otherwise} \end{cases} \cong H_n^\Delta(X^k, X^{k-1}).$$

We claim that $H_n(X^k, X^{k-1})$ are also **free Abelian** on the **singular k -simplices** defined by the characteristic maps $\Delta^k \rightarrow X^k$ when $n = k$, and 0 otherwise. Consider the map

$$\Phi: \coprod_{\alpha} (\Delta_{\alpha}^k, \partial \Delta_{\alpha}^k) \rightarrow (X^k, X^{k-1})$$

defined by the characteristic map. This induces an isomorphism on **homology** since

$$\coprod_{\alpha} \Delta_{\alpha}^k / \coprod_{\alpha} \partial \Delta_{\alpha}^k \xrightarrow{\cong} X^k / X^{k-1}.$$

This reduces to check that

$$H_n(\Delta^k, \partial \Delta^k) = \begin{cases} 0, & \text{if } n \neq k; \\ \mathbb{Z}, & \text{if } n = k \end{cases}$$

generated by the identity map $\Delta^k \rightarrow \Delta^k$. ■

Corollary 5.5.1. If X has a **Δ -complex** structure (or is **homotopy equivalent** to one), then we have the followings.

- (1) If the dimension is $\leq d$, then $H_n(X) = 0$ for all $n > d$.
- (2) If \bar{X} has no **cells** of dimension p , then $H_p(X) = 0$.
- (3) If \bar{X} has no **cells** of dimension p , then $H_{p-1}(X)$ is **free Abelian**.

Corollary 5.5.2. Given a **singular homology class** on X , without loss of generality we can choose a **Δ -complex** structure on X , and we then we can assume the **class** is represented by a **simplicial n -cycle**.

Remark. Recall the definition of **homology class**, as we noted before, this means we can view **singular chain complex** as some kind of geometric subjects. The construction can be found in Hatcher[HPM02].

5.6 Degree

Definition 5.6.1 (Degree). Let $f: S^n \rightarrow S^n$, then

$$f_*: \mathbb{Z} \cong H_n(S^n) \rightarrow H_n(S^n) \cong \mathbb{Z}$$

is a multiplication by some integer^a $d \in \mathbb{Z}$, which we call it as the *degree*, denotes as $\deg(f)$ of f .

^aThis just follows from group theory.

is a multiplication by some integer^a $d \in \mathbb{Z}$, which we call it as the *degree*, denotes as $\deg(f)$ of f .

Remark (Properties of Degree). We first see some properties of `degree`.

- (1) $\deg(\mathrm{id}_{S^n}) = 1$ since $(\mathrm{id}_{S^n})_* = \mathrm{id}_{\mathbb{Z}}$.
- (2) If $f: S^n \rightarrow S^n$, $n \geq 0$ is not surjective, then $\deg(f) = 0$. To see this, we know that f_* factors as

$$H_n(S^n) \longrightarrow H_n(S^n - \{*\}) = 0 \longrightarrow H_n(S^n)$$

f_*

And since the middle group is zero because $S^n \setminus \{*\}$ is **contractible**, $f_* = 0$, so is its **degree**.

- (3) If $f \simeq g$, then $f_* = g_*$, so $\deg(f) = \deg(g)$.

Note. The converse is true! We'll see this later.

- (4) $(f \circ g)_* = f_* \circ g_*$, and so $\deg(f \circ g) = \deg(f) \deg(g)$. Consequently, if f is a [homotopy equivalence](#) then $f \circ g \simeq \text{id}$, hence

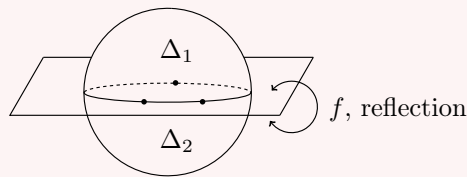
$$\deg f \deg g = \deg \text{id} = 1,$$

so $\deg f = \pm 1$.

- (5) If f is a reflection fixing the equator, and swapping the 2-cells, then $\deg f = -1$.

Exercise. It is possible to put a Δ -complex structure with 2 n -cells, Δ_1 and Δ_2 glued together along their boundary ($\cong S^{n-1}$), and

$$H_n(S^n) = \langle \Delta_1 - \Delta_2 \rangle.$$



Answer. By doing so, we see that the reflection f interchanges Δ_1 and Δ_2 , hence the generator is now its negative. *

- (6) We now have the following linear algebra exercise.

Exercise. The antipodal map $-\text{id}: S^{n+1} \rightarrow S^{n+1}$ given by $x \mapsto -x$ is the composite of $(n+1)$ reflections.

So the antipodal map $-\text{id}: S^n \rightarrow S^n$ given by $x \mapsto -x$ has **degree** which is the product of $n + 1$ copies of (-1) , and so it has **degree** $(-1)^{n+1}$. (i.e., since the $(n + 1) \times (n + 1)$ scalar matrix (-1) is composition of $(n + 1)$ reflections.)

- (7) We see the following.

Exercise. If $f: S^n \rightarrow S^n$ has no fixed points, then we can homotope f to the antipodal map via

$$f_t(x) = \frac{(1-t)f(x) - tx}{\|(1-t)f(x) - tx\|}.$$

Therefore, $\deg f = (-1)^{n+1}$.

Lecture 30: Degree

With the definition of [degree](#) and some of its [properties](#), we have the following theorems.

23 Mar. 10:00

Theorem 5.6.1 (Hairy ball theorem). The sphere S^n admits a nonvanishing continuous tangent vector field if and only if n is odd.

Proof. Recall that a tangent vector field to the unit sphere $S^n \subseteq \mathbb{R}^{n+1}$ is a continuous map

$$v: S^n \rightarrow \mathbb{R}^{n+1}$$

such that $v(x)$ is tangent to S^n at x , i.e., $v(x)$ is perpendicular to the vector x for each x . Let $v(x)$ be a nonvanishing tangent vector field on the sphere S^n , then we define

$$f_t(x) := \cos(\pi t) + \sin(\pi t) \left(\frac{v(x)}{\|v(x)\|} \right),$$

which is a [homotopy](#) from the identity map $\text{id}_{S^n}: S^n \rightarrow S^n$ to the antipodal map $-\text{id}_{S^n}: S^n \rightarrow S^n$. This simply follows from varying t from 0 to 1, where we have

$$f_0(x) = \cos(0)x + \sin(0) \left(\frac{v(x)}{\|v(x)\|} \right) = x \Rightarrow f_0 = \text{id}_{S^n},$$

while

$$f_1(x) = \cos(\pi)x + \sin(\pi) \left(\frac{v(x)}{\|v(x)\|} \right) = -x \Rightarrow f_1 = -\text{id}_{S^n}.$$

The last thing needs to be verified is that $f_t(x)$ is continuous, but this is trivial.

From the [property of degree](#), we know that it's a [homotopy](#) invariant, hence

$$\deg(-\text{id}_{S^n}) = \deg(\text{id}_{S^n}),$$

which implies

$$(-1)^{n+1} = 1,$$

so n must be odd.

Conversely, if n is odd, say $n = 2k - 1$, we can define

$$v(x_1, x_2, \dots, x_{2k-1}, x_{2k}) = (-x_2, x_1, \dots, -x_{2k}, x_{2k-1}).$$

Then $v(x)$ is orthogonal to x , so v is a tangent vector field on S^n , and $\|v(x)\| = 1$ for all $x \in S^n$. ■

Theorem 5.6.2 (Groups acting on S^{2n}). If G acts on S^{2n} [freely](#), then

$$G = \mathbb{Z}/2\mathbb{Z} \text{ or } 1.$$

Proof. There exists a homomorphism given by

$$\begin{aligned} d: G &\rightarrow \{\pm 1\} \\ g &\mapsto \deg(\tau_g) \end{aligned}$$

Where τ_g is the action of $g \in G$ on S^{2n} as a map $S^{2n} \rightarrow S^{2n}$. We know this map is well-defined

since τ_g is invertible (simply take $\tau_{g^{-1}}$) for each $g \in G$. Also, we see that $d(g_1 g_2) = d(g_1) \cdot d(g_2)$, hence it is a homomorphism.

We want to show that the kernel is trivial, since then by the first isomorphism theorem $G \cong \text{Im}$, and the image is either trivial or $\mathbb{Z}/2\mathbb{Z}$. Suppose that g is a nontrivial element of G , then since G acts **freely** we know that τ_g has no fixed points. With this in mind we have

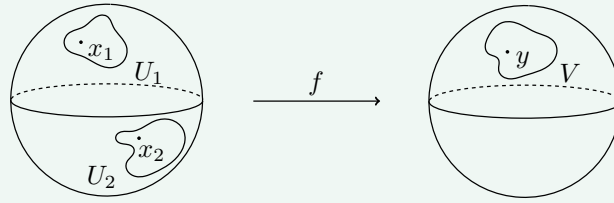
$$\deg \tau_g = (-1)^{2n+1} = -1.$$

Thus, $g \notin \ker$, hence the kernel is trivial as desired. \blacksquare

Corollary 5.6.1. S^{2n} has only the trivial **cover** $S^{2n} \rightarrow S^{2n}$ or degree 2 **cover** (for example, $S^{2n} \rightarrow \mathbb{R}P^{2n}$).

Proof. This follows since any **covering space** action acts **freely**, then we simply apply **Theorem 5.6.2**. \blacksquare

Definition 5.6.2 (Local degree). Let $f: S^n \rightarrow S^n$ ($n > 0$). Suppose there exists $y \in S^n$ such that $f^{-1}(y)$ is finite, say, $\{x_1, \dots, x_m\}$. Then let U_1, \dots, U_m be disjoint neighborhoods of x_1, \dots, x_m that are mapped by f to some neighborhood V of y .



The *local degree* of f at x_i , denote as $\deg f|_{x_i}$, is the **degree** of the map

$$f_*: \mathbb{Z} \cong H_n(U_i, U_i - \{x_i\}) \rightarrow H_n(V, V - \{y\}) \cong \mathbb{Z}.$$

Remark. The homomorphism f_* is a multiplication by an integer, which is the **local degree** as we just defined, arises from the following natural diagram.

$$\begin{array}{ccccc}
 & H_n(U_i, U_i - \{x_i\}) & \xrightarrow{f_*} & H_n(V, V - \{y\}) & \\
 & \uparrow \cong & & \downarrow \cong & \\
 H_n(S^n, S^n - \{x_i\}) & \xleftarrow{p_i} & H_n(S^n, S^n - f^{-1}(y)) & \xrightarrow{f_*} & H_n(S^n, S^n - \{y\}) \\
 & \downarrow \cong & & \uparrow \cong & \\
 & H_n(S^n) & \xrightarrow{f_*} & H_n(S^n) &
 \end{array}$$

(Note: The diagram above is a simplified representation of the commutative diagram in the image. The actual diagram includes vertical maps k_i and j connecting the middle and bottom rows, and isomorphisms connecting the top and bottom rows.)

The two isomorphisms in the upper half come from **excision**, and the lower two isomorphisms come from **exact sequences of pairs**.

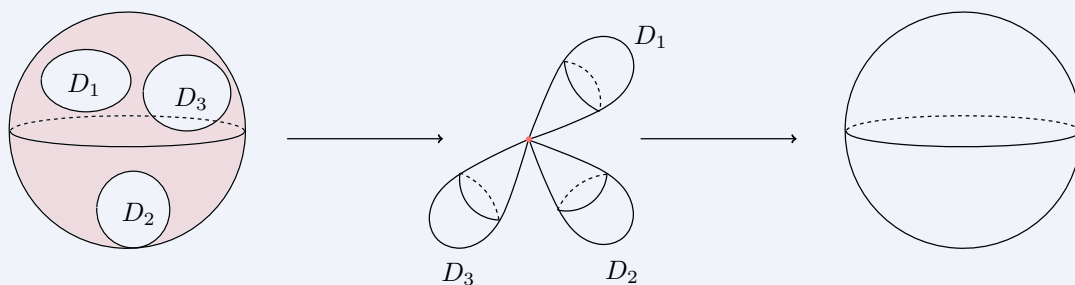
Theorem 5.6.3. Let $f: S^n \rightarrow S^n$ with $f^{-1}(y) = \{x_1, \dots, x_m\}$ as in **Definition 5.6.2**, then we have

$$\deg f = \sum_{i=1}^m \deg f|_{x_i}.$$

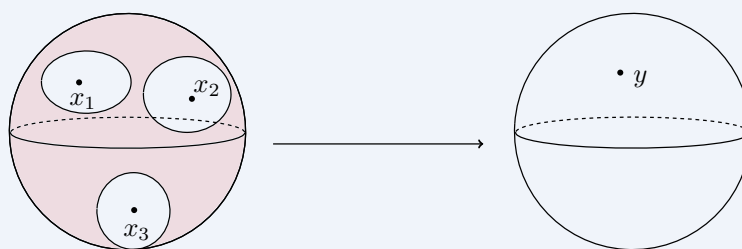
Remark. Thus, we can compute the **degree** of f by computing these **local degrees**.

Let's work with some examples for our edification.

Example. Consider S^n and choose m disks in S^n . Namely, we first collapse the complement of the m disks to a point, and then we identify each of the m disks with the n -sphere itself.



The result will be a map of degree m . We can see this by computing local degree.



By choosing a good point in the codomain, we get one point for each disk in the preimage, and the map is a local homeomorphism around these points which is orientation preserving. We could likewise compose the maps to S^n from the wedge with a reflection to construct a map of degree $-m$.

Remark. We see that from the above construction, we can produce a map $S^n \rightarrow S^n$ in any degree.

Lecture 31: Local Degree and Local Homology

We first see another example of the application of Theorem 5.6.3.

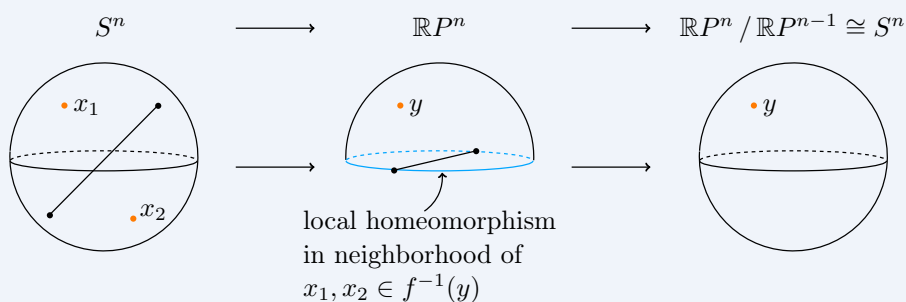
25 Mar. 10:00

Example. Consider the composition of the quotient maps below

$$S^n \xrightarrow{\quad} \mathbb{R}P^n \xrightarrow{\quad} \mathbb{R}P^n / \mathbb{R}P^{n-1} \cong S^n$$

f

We want to compute the degree of this map.



Note that this restricts to a homeomorphism on each component of $S^n \setminus \text{equator}$ as a map to $\mathbb{R}P^n / \mathbb{R}P^{n-1}$. Suppose we've oriented our copies of S^n in such a way that the homeomorphism on the top hemisphere is orientation-preserving. The homeomorphism on the bottom hemisphere is given by taking the antipodal map and composing with the homeomorphism of the top hemisphere

$$\deg = \deg(\text{id}) = \deg(\text{antipodal}) = 1 + (-1)^{n+1} = \begin{cases} 0, & \text{if } n \text{ even;} \\ 2, & \text{if } n \text{ odd.} \end{cases}$$

We can now prove [Theorem 5.6.3](#).

Proof of Theorem 5.6.3. If $f: S^n \rightarrow S^n$ and we have some $y \in S^n$ with $f^{-1}(\{y\}) = \{x_1, \dots, x_m\}$, then we have a nice commutative diagram as follows.

$$\begin{array}{ccc}
 H_n(S^n) & \xrightarrow{f_*} & H_n(S^n) \\
 \text{LES of pair} \downarrow & & \downarrow \cong \text{LES of a pair} \\
 \bigoplus_{i=1}^m \mathbb{Z} = H_n(S^n, S^n - \{x_1, \dots, x_m\}) & & H_n(S^n, S^n - \{y\}) \\
 \text{excision} \uparrow \cong & & \uparrow \cong \text{excision} \\
 H_n\left(\coprod_{i=1}^m U_i, \coprod_{i=1}^m (U_i - \{x_i\})\right) & & H_n(V, V - \{y\}) \\
 \text{homology of disjoint union} \uparrow \cong & & \uparrow \cong \\
 \bigoplus_i H_n(U_i, U_i - \{x_i\}) & \xrightarrow{\quad} & H_n(V, V - \{y\})
 \end{array}$$

$$\begin{array}{ccc}
 1 & \xrightarrow{\quad} & \deg(f_*) \\
 \downarrow & & \downarrow \\
 (1, 1, \dots, 1) & \xrightarrow{\quad} & \deg f = \sum \deg f|_{x_i}
 \end{array}$$

where we trace around the outside of the diagram at the bottom, which just proves the result. ■

With [degree](#), we have a very efficient way for computing the [homology groups](#) of [CW complexes](#), which is so-called [cellular homology](#). But before we dive into this, we first grab some intuition about the essential of which, namely,

what really is local homology?

Problem 5.6.1. What is local homology?

Answer. By [excision](#), there is an isomorphism $H_n(S^n, S^n \setminus \{x_i\}) \cong H_n(U, U \setminus \{x_i\})$ for any open neighborhood U of x_i .

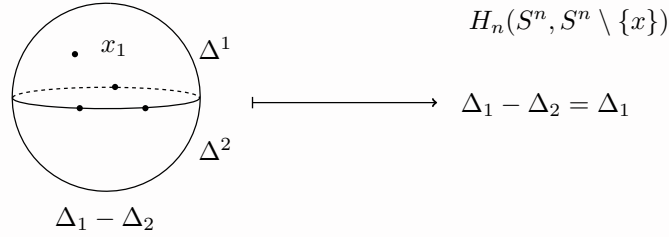
The long [exact sequence](#) of a [pair](#) also gives us

$$\dots \rightarrow H_k(S^n \setminus \{x_i\}) \rightarrow H_k(S^n) \rightarrow H_k(S^n, S^n \setminus \{x_i\}) \rightarrow H_{k-1}(S^n \setminus \{x_i\}) \rightarrow \dots$$

Since $S^n \setminus \{x_i\}$ is homeomorphic to an open n -ball, we see that $H_k(S^n \setminus \{x_i\}) = H_{k-1}(S^n \setminus \{x_i\}) = 0$. With this in mind, j_* is an isomorphism.

We want to think about what j_* does when $k = n$, i.e., when this is an isomorphism $\mathbb{Z} \cong H_n(S^n) \rightarrow H_n(S^n, S^n \setminus \{x_i\}) \cong \mathbb{Z}$.

We see that $\Delta_1 - \Delta_2$ generate $H_n(S^n)$, where Δ_1, Δ_2 are the top and bottom hemisphere indicated below.



We then understand that $j_*(\Delta_1 - \Delta_2) = \Delta_1 - \Delta_2 = \Delta_1$ since $\Delta_2 = 0$ in $C_n(S^n)/C_n(S^n \setminus \{x_i\})$. The upshot is that $H_n(S^n, S^n \setminus \{x\})$ is generated by an n -simplex with x in its interior.

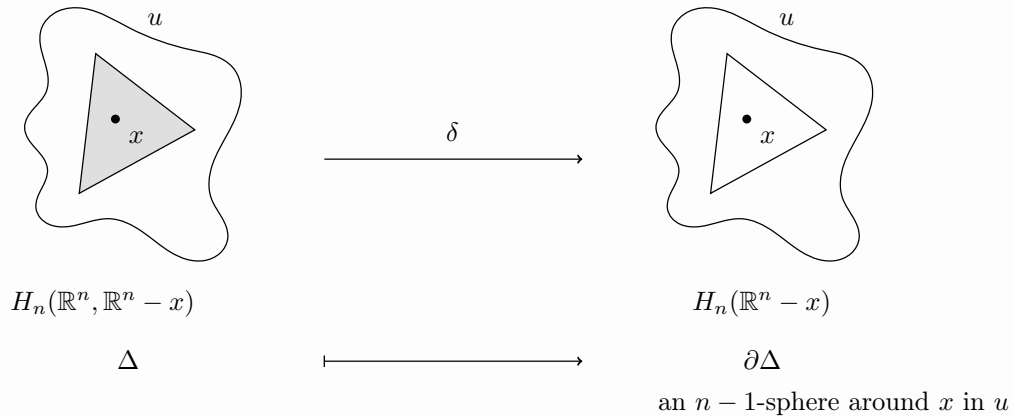
Suppose M is an n -manifold. Then $H_n(M, M \setminus \{x\}) \cong H_n(U, U \setminus \{x\})$, where U is a small ball around x . Because U is a ball homeomorphic to \mathbb{R}^n , we see that

$$H_n(M, M \setminus \{x\}) \cong H_n(U, U \setminus \{x\}) \cong H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\}).$$

By the long exact sequence of a pair

$$0 = H_n(\mathbb{R}^n) \rightarrow H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\}) \rightarrow H_{n-1}(\mathbb{R}^n \setminus \{x\}) \rightarrow H_{n-1}(\mathbb{R}^n) = 0$$

And since $\mathbb{R}^n \setminus \{x\}$ is homotopy equivalent to an $n-1$ sphere, this means that $H_n(\mathbb{R}^n, \mathbb{R}^n \setminus \{x\}) \cong \mathbb{Z}$. By homework, this connecting homomorphism is given by taking the boundary of a relative cycle as below.



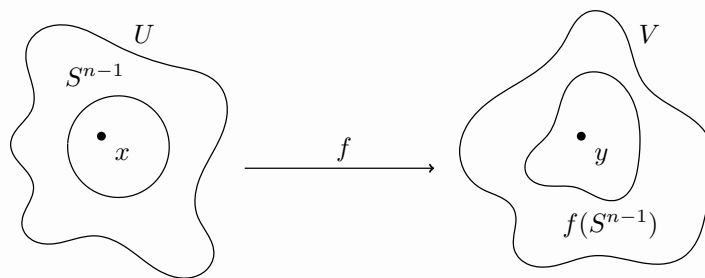
We intuitively want to use this idea to compute degree using this idea. We use naturality of the long exact sequence, namely the fact that where $f: (U_i, U_i \setminus \{x_i\}) \rightarrow (V, y)$ is a map of pairs, then the following diagram commutes.

$$\begin{array}{ccccccc} \dots & \longrightarrow & H_n(U_i, U_i \setminus \{x_i\}) & \longrightarrow & H_{n-1}(U_i, U_i \setminus \{x_i\}) & \longrightarrow & \dots \\ & & \downarrow f_* & & \downarrow f_* & & \\ \dots & \longrightarrow & H_n(V, V \setminus \{y\}) & \longrightarrow & H_{n-1}(V, V \setminus \{y\}) & \longrightarrow & \dots \end{array}$$

By naturality of the long exact sequence and the isomorphism discussed above, we can compute the local degree of a map $S^n \rightarrow S^n$ at a point x by computing the degree of the map

$$H_{n-1}(U \setminus \{x\}) \longrightarrow H_{n-1}(V \setminus \{y\})$$

In fact the local degree will be the degree restricted to a small S^{n-1} in the neighborhood U .



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Example (Degree of z^n). Consider

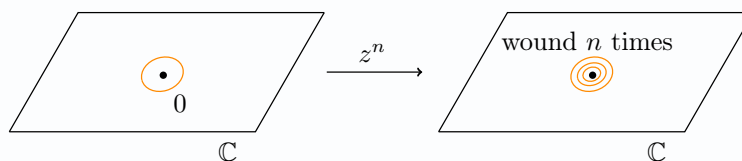
$$f: \tilde{\mathbb{C}} \rightarrow \tilde{\mathbb{C}}$$

$$z \mapsto z^n.$$

We see that

$$\deg f|_0 = n.$$

Proof. We look at the illustration of $f(z) = z^n$.



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Lecture 32: Cellular Homology

5.7 Cellular Homology

28 Mar. 10:00

Suppose that X is a **CW complex**, then (X^n, X^{n-1}) is a **good pair** for all $n > 1$, and X^n / X^{n-1} is a **wedge of n -spheres**, one for each **n -cell** e_α^n . Hence,

$$H_k(X^n, X^{n-1}) \cong \begin{cases} 0, & \text{if } k \neq n; \\ \langle e_\alpha^n \mid e_\alpha^n \text{ is an } n\text{-cell} \rangle, & \text{if } k = n. \end{cases}$$

Definition 5.7.1 (Cellular chain complex). The *cellular chain complex* on X is the **chain complex** with **cellular chain group** and **cellular boundary map** defined as follows.

Definition 5.7.2 (Cellular chain group). The **chain groups** $C_n(X)$ defined as

$$C_n(X) := \mathbb{Z} \langle e_\alpha^n \mid e_\alpha^n \text{ an } n\text{-cells of } X \rangle (\cong H_n(X^n, X^{n-1}))$$

with $X^{-1} = \emptyset$ is called *cellular chain group*.

Definition 5.7.3 (Cellular boundary map). For $n = 0$, we have

$$\begin{aligned}\partial_1: C_1(X) &\rightarrow C_0(X) \\ \langle \text{1-cell} \rangle &\rightarrow \langle \text{0-cell} \rangle,\end{aligned}$$

which is the usual [simplicial boundary map](#).^a For $n > 1$, the [boundary map](#) ∂_n are defined as

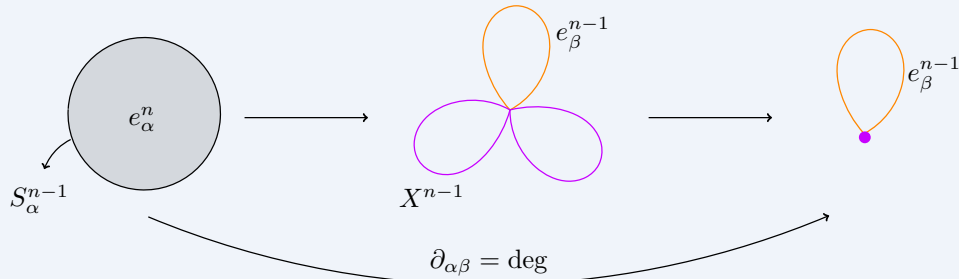
$$\partial_n(e_\alpha^n) = \sum_{\beta} \partial_{\alpha\beta} e_\beta^{n-1}$$

where $\partial_{\alpha\beta}$ is the [degree](#) of the map

$$\partial e_\alpha^n = S_\alpha^{n-1} \xrightarrow[\text{map}]{\text{attaching}} X^{n-1} \xrightarrow[X^{n-1} \setminus e_\beta^{n-1}]{\text{quotient by}} S_\beta^{n-1}$$

^ai.e., $\partial_1: C_1(X) = H_1(X^1, X^0) \rightarrow C_0(X) = H_0(X^0)$ is just $\Delta_1(X) \rightarrow \Delta_0(X)$.

Example. In pictures, the [degree](#) of a function is given as the following.



Remark. We see that

$$C_n(X) \cong H_n(X^n, X^{n-1})$$

since (X^n, X^{n-1}) is a [good pair](#), so $H_n(X^n, X^{n-1}) \cong H_n(X^n / X^{n-1})$, which is just the [wedge](#) of 1 n -sphere for each n -cell of X .

Furthermore, the orientations on spheres are defined by identifying the domains of characteristic maps $D_\alpha^n \rightarrow X$ with an (oriented) disk in \mathbb{R}^n . i.e., we need to choose a generator of

$$H_{n-1}(\partial D_\alpha^n) \cong H_{n-1}(S^{n-1}) \cong \mathbb{Z}.$$

Note. In Hatcher[HPM02], the approach of the definition of [cellular chain complex](#) is a bit different, especially for how we define the boundary maps. Here we simply define $\partial_n(e_\alpha^n) := \sum_{\beta} \partial_{\alpha\beta} e_\beta^{n-1}$, where this is so-called *cellular boundary formula* in Hatcher[HPM02]. Here, we just defined ∂_n in this way instead, but we should still check that this is well-defined of this definition. The proof is given in [Appendix A.3](#).

Definition 5.7.4 (Cellular homology group). We define the so-called *cellular homology group* by [cellular chain complex](#) in our usual way of defining [homology group](#).

Remark. We sometimes denote the [cellular homology group](#) as $H_n^{\text{CW}}(X)$ if it causes confusion.

Theorem 5.7.1. [Definition 5.7.1](#) indeed forms a [chain complex](#).

Proof. We need to check two things, namely the chain group $H_n(X^n, X^{n-1})$ defined in Definition 5.7.1 is indeed free Abelian with basis in each n -cell. But this is trivial since we have an one-to-one correspondence with the n -cells of X as we have shown, and we can think of elements of $H_n(X^n, X^{n-1})$ as linear combinations of n -cells of X .

The fact that the boundary map defined in Definition 5.7.1 has the property $\partial^2 = 0$ will be proved in Theorem 5.7.2. ■

Theorem 5.7.2 (Cellular homology agrees with singular homology). The cellular homology groups coincide with the singular homology groups, i.e.,

$$H_n^{\text{CW}}(X) \cong H_n(X).$$

Note. i.e., the isomorphism commutes $\bar{\omega}f_*$ for all continuous $f: X \rightarrow Y$.

Theorem 5.7.2 implies the following.

Corollary 5.7.1. We have the followings.

- $H_n(X) = 0$ if X has a CW complex structure with no n -cells.
- If X has a CW complex with k n -cells, then $H_n(X)$ is generated by at most k elements.
- If $H_n(X)$ is a group with a minimum of k generators, then any CW complex structure on X must have at least k n -cells.
- If X has a CW complex with no n -cells, then

$$H_{n-1}(X) = \ker(\partial_{n-1}),$$

which is free Abelian.

- If X has a CW complex with no cells in consecutive dimensions, then all $\partial_n = 0$. Its homology are free Abelian on its n -cells, namely the cellular chain groups.

Example. The last point in Corollary 5.7.1 is quite useful, as the following examples will show.

- (1) $S^n, n \geq 2$. Since if we have S^n with $n \geq 2$, using the CW complex structure of e^n attached to a single point x_0 . The cellular chain complex is given as

$$0 \longrightarrow 0 \longrightarrow \langle e^n \rangle \longrightarrow 0 \longrightarrow \dots \longrightarrow 0 \longrightarrow \langle x_0 \rangle \longrightarrow 0$$

So then all the boundary maps are zero, and we see that

$$H_k(S^n) = \begin{cases} \mathbb{Z}, & \text{if } k = 0, n; \\ 0, & \text{otherwise.} \end{cases}$$

- (2) $\mathbb{C}P^n, \forall n$. In this case, we can let $\mathbb{C}P^n$ equipped with a CW complex structure with one cell of each even dimension $2k \leq 2n$, thus

$$H_k(\mathbb{C}P^n) \cong \begin{cases} \mathbb{Z}, & \text{if } k = 0, 2, \dots, 2n; \\ 0, & \text{otherwise.} \end{cases}$$

- (3) $S^n \times S^n, n > 1$. We let $S^n \times S^n$ has the product CW structure consisting of a 0-cell, two

n -cells, and a $2n$ -cell. Thus, we have

$$H_k(\mathbb{C}P^n) \cong \begin{cases} \mathbb{Z}, & \text{if } k = 0, 2n; \\ \mathbb{Z}^2, & \text{if } k = n; \\ 0, & \text{otherwise.} \end{cases}$$

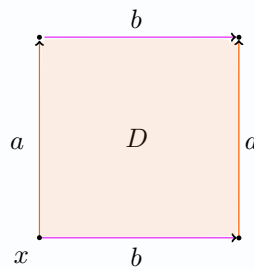
Exercise. Redo this calculation for S^n with other CW complex structures on S^n , e.g. glue 2 k -cells onto S^{k-1} and proceed inductively.

Lecture 33: Cellular Homology Examples

Example (Cellular homology group of torus). Calculate the cellular homology group of a torus.

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Proof. Let the torus equips with the following CW complex structure.



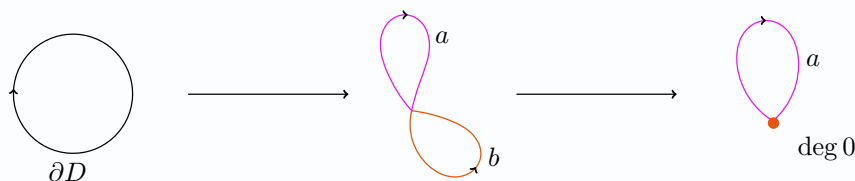
The cellular chain complex looks like

$$0 \longrightarrow \langle D \rangle \longrightarrow \langle a, b \rangle \longrightarrow \langle x \rangle \longrightarrow 0$$

where we choose x as a base point (i.e. the 0-cell).

For ∂_1 , since this is defined as the same as the usual simplicial boundary map, hence by $a \mapsto x - x = 0$ and $b \mapsto x - x = 0$, we have $\partial_1 = 0$.

Now for ∂_2 , since D is glued along $aba^{-1}b^{-1}$, so we look at the composed up maps



We wind forwards then backwards around a , so the degree is zero. The same thing happens for b , so

$$\partial_2 D = \underbrace{0 \cdot a}_{\partial_{\alpha\beta_a} a} + \underbrace{0 \cdot b}_{\partial_{\alpha\beta_b} b} = 0,$$

where we assume that α is the index of D , and β_a is the index of a and same for b .

This gives a nice **principle**, namely if a 2-cells D is glued down via some words w (this only makes sense for 2-cells), then the coefficient^b to a letter a in $\partial_2 D$ is the sum of the exponents of a in w . In this case, for both a and b , the coefficients for are both $1 + (-1) = 0$.

Now we just have that the homology groups are equal to the chain groups because the boundary

maps are all zero. Hence, we have

$$H_k(T) = \begin{cases} \mathbb{Z}, & \text{if } k = 0, 2; \\ \mathbb{Z}^2, & \text{if } k = 1; \\ 0, & \text{otherwise.} \end{cases}$$

⊛

^aIntuitively, since we **quotient** out b , hence the gluing map is **homotopy** to constant maps.
^bi.e. $\partial_{\alpha\beta}(a)$ where α is the index of a .

Example (Cellular homology group of Σ_g). Calculate the **cellular homology group** of a genus g surface Σ_g .

Proof. A genus g surface Σ_g has the **CW complex** structure as

- 1 **0-cell** x .
- $2g$ **1-cells** $a_1, b_1, a_2, b_2, \dots$
- 1 **2-cell** D glued along $[a_1, b_1][a_2, b_2] \cdots [a_g, b_g]$ (a product of commutators)

For ∂_1 , we have

$$\partial_1(a_i) = \partial_1(b_i) = x - x = 0.$$

Furthermore, by the principle discussed above, we know that every **1-cell** appears once in the **word**, and its inverse appears once, so all the coefficients of **1-cells** in $\partial_2(D)$ are zero, so $\partial_2(D) = 0$. This means we have a **chain complex**

$$0 \longrightarrow \mathbb{Z} \xrightarrow{0} \mathbb{Z}^{2g} \xrightarrow{0} \mathbb{Z} \longrightarrow 0$$

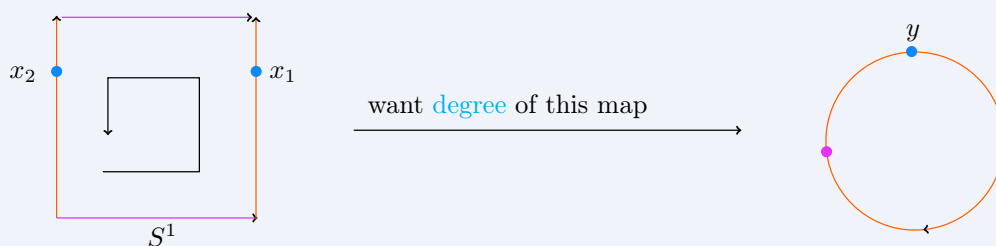
And so then we have that

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

⊛

Exercise. Calculate the **cellular homology group** of $\mathbb{R}P^n$.

Example (Torus example: ∂_2 in more detail). We're going to work through this example a bit more carefully.



Let's zoom in on these two preimage points and use *local homology* to compute this:

Fill this up!

Lecture 34: Proof of Theorem 5.7.2

1 Apr. 10:00

We're now going to work towards proving that [cellular homology agrees with singular homology](#). First we need some nontrivial preliminaries.

Lemma 5.7.1. We have that

- (1) $H_k(X^n, X^{n-1}) = \begin{cases} 0, & \text{if } k \neq n; \\ \langle n\text{-cells} \rangle, & \text{if } k = n. \end{cases}$
- (2) $H_k(X^n) = 0$ for all $k > n$. If X is finite dimensional, then $H_k(X^n) = 0$ for all $k > \dim X$.
- (3) The inclusion $X^n \hookrightarrow X$ induces $H_k(X^n) \rightarrow H_k(X)$. Then this map is
 - an isomorphism for $k < n$
 - surjective for $k = n$
 - zero for $k > n$.

Proof. For (1), we see that

$$X^n / X^{n-1} \cong \text{wedge of one } n\text{-sphere for each } n\text{-cell}.$$

The result then follows from [Theorem 5.5.5](#) and its immediately corollary, namely

$$\bigoplus_{\alpha} \tilde{H}_n(X_{\alpha}) \cong \tilde{H}_n \left(\bigvee_{\alpha} X_{\alpha} \right)$$

provided that the [wedge sum](#) is formed at basepoints $x_{\alpha} \in X_{\alpha}$ such that (X_{α}, x_{α}) are [good](#), and then we simply consider $(X, A) = (\coprod_{\alpha} X_{\alpha}, \coprod_{\alpha} \{x_{\alpha}\})$.

Now we prove (2) and (3). We consider the [long exact sequence of a pair](#) for fixed n ,

$$\begin{array}{ccccccc} \dots & \longrightarrow & H_{k+1}(X^n, X^{n-1}) & \longrightarrow & H_k(X^{n-1}) & & \\ & & & \searrow \cong & & & \\ & & H_k(X^n) & \longrightarrow & H_k(X^n, X^{n-1}) & \longrightarrow & \dots \end{array}$$

When $k+1 < n$ or $k > n$ then $H_{k+1}(X^n, X^{n-1}) = 0$ and $H_k(X^{n-1}) = 0$, so the above map $H_k(X^{n-1}) \rightarrow H_k(X^n)$ is an isomorphism. We also get sequences telling us the injective and surjective maps when $k = n$ or $k = n-1$,

$$\begin{array}{ccccccc} \dots & \longrightarrow & 0 = H_{n+1}(X^n, X^{n-1}) & \longrightarrow & H_n(X^{n-1}) & \longrightarrow & H_n(X^n) \\ & & & & \swarrow & & \\ & & H_n(X^n, X^{n-1}) & \longrightarrow & H_{n-1}(X^{n-1}) & \longrightarrow & H_{n-1}(X^n) \\ & & & & \swarrow & & \\ & & H_{n-1}(X^n, X^{n-1}) = 0 & \longrightarrow & \dots & & \end{array}$$

So the maps $H_n(X^{n-1}) \rightarrow H_n(X^n)$ is injective, and the map $H_{n-1}(X^{n-1}) \rightarrow H_{n-1}(X^n)$ is surjective.

Fix k , then we get a pile of maps induced by the inclusions $X^n \hookrightarrow X^{n+1}$

$$\begin{array}{ccccccc} H_k(X^0) & \xrightarrow{\cong} & H_k(X^1) & \xrightarrow{\cong} & H_k(X^2) & \xrightarrow{\cong} & \dots \\ & & & & \searrow \cong & & \\ & & H_k(X^{k-1}) & \xrightarrow{\text{inj.}} & H_k(X^k) & \xrightarrow{\text{surj.}} & H_k(X^{k+1}) \\ & & & & \searrow \cong & & \\ & & H_k(X^{k+2}) & \xrightarrow{\cong} & H_k(X^{k+3}) & \xrightarrow{\cong} & \dots \end{array}$$

Note. This sequence is not [exact](#). Descriptions of maps (in [red](#)) follow from our analysis of the [long exact sequence of a pair](#) above.

To prove (2),

- $k = 0$, we do this by hand.
- $k \geq 1$, then $H_k(X^0) = 0$, so we have that $H_k(X^0), \dots, H_k(X^{k-1})$ are all zero from the isomorphisms above. That is the k -th [homology](#) $H_k(X^n) = H_k(X^n)$ is zero for every [\$n\$ -skeleton](#) where $n < k$, just as desired.

We also have the following collection of maps for fixed k

$$H_k(X^k) \xrightarrow{\text{surj.}} H_k(X^{k+1}) \xrightarrow{\cong} H_k(X^{k+2}) \xrightarrow{\cong} \dots$$

This implies (3) when X is finite dimensional. For general X , we use the fact that every [simplex](#) has image contained in some finite [skeleton](#) (since image is compact). ■

Exercise. Check (2) and (3) in [Lemma 5.7.1](#) directly in the case that the [CW complex](#) structure is a Δ -[complex](#) using [simplicial chains](#).

We now prove [Theorem 5.7.2](#).

Proof of Theorem 5.7.2. We get some [exact sequences](#) from our [preliminaries](#),

$$0 = H_{n+1}(X^n) \longrightarrow H_n(X^n) \longrightarrow H_n(X^n, X^{n+1}) \longrightarrow H_{n-1}(X^n, X^{n+1})$$

$$H_{n+1}(X^{n+1}, X^n) \longrightarrow H_n(X^n) \longrightarrow H_n(X^{n+1}) \longrightarrow H_n(X^{n+1}, X^n) = 0$$

These come from the [long exact sequences of a pair](#) combined with the things we've deduced in the [preliminaries](#). We can paste these together into a diagram, we have

$$\begin{array}{ccccccc}
 & & & & & & 0 \\
 & & & & & \nearrow & \\
 & & & & H_n(X^{n+1}) \cong H_n(X) & & \\
 & & \nearrow & & \searrow & & \\
 0 & & H_n(X^n) & & & & \\
 & \nearrow \partial_{n+1} & \searrow j_n & & & & \\
 \dots \rightarrow H_{n+1}(X^{n+1}, X^n) & \xrightarrow{d_{n+1}} & H_n(X^n, X^{n+1}) & \xrightarrow{d_n} & H_{n-1}(X^n, X^{n+1}) & \rightarrow \dots \\
 & & \searrow \partial_n & & \nearrow j_{n-1} & & \\
 & & H_{n-1}(X^{n+1}) & & & & \\
 & & \nearrow & & & & 0
 \end{array}$$

Hatcher[HPM02] tells us this diagram commutes, and what we've done here tells us that the two red diagonal pieces crossing at $H_n(X^n)$ are [exact](#). We also have [exactness](#) of the bottom right diagonal by just going down a degree.

Then the horizontal row has to at least be a [chain complex](#) since the diagram commutes, and we have

$$d_n \circ d_{n+1} = (j_{n-1} \circ \underbrace{\partial_n \circ j_n}_0 \circ \partial_{n+1}) = 0,$$

hence we see that $d^2 = 0$.^a

By [exactness](#), we know that if $\iota_*: H_n(X^n) \rightarrow H_n(X^{n+1})$, then using the first isomorphism theorem,

$$H_n(X) \cong H_n(X^{n+1}) = \text{Im } \iota_* \cong H_n(X^n) / \ker \iota_* = H_n(X^n) / \text{Im } \partial_{n+1}.$$

Since j_n injects by [exactness](#),

$$\begin{aligned} j_n : H_n(X^n) &\xrightarrow{\cong} j_n(H_n(X^n)) \\ \text{Im } \partial_{n+1} &\xrightarrow{\cong} \text{Im}(j_n \circ \partial_{n+1}) = \text{Im } d_{n+1}, \end{aligned}$$

so j_{n-1} must also inject by [exactness](#), and by applying [exactness](#), we have

$$\ker d_n = \ker \partial_n = \text{Im } j_n.$$

Then we just do some group theory, the n -th [cellular homology group](#) is

$$\ker d_n / \text{Im } d_{n+1} \cong \text{Im } j_n / \text{Im}(j_n \circ \partial_{n+1}) \cong H_n(X^n) / \text{Im } \partial_{n+1} \cong H_n(X).$$

There is one thing left to show, namely commutativity of this map. We claim that the differentials $d_n = j_n \circ \partial_{n+1}$ satisfy the formula (in terms of degree) that we stated. This is done by direct analysis of definitions of maps; details in Hatcher[HPM02]. ■

^aThis is the missing part of the proof of [Theorem 5.7.1](#).

Lecture 35: Eilenberg-Steenrod Axioms

5.8 Eilenberg-Steenrod Axioms

4 Apr. 10:00

We can approach the homology theory in an **axiomatic** way. Specifically, we're interested in the Eilenberg-Steenrod axioms. To start with, we first see some definitions.

Definition 5.8.1 (Natural transformation). Given two [functors](#)

$$F, G : \mathcal{C} \rightarrow \mathcal{D},$$

a *natural transformation* $\eta : F \rightarrow G$ is a collection of maps $\eta_X : F(X) \rightarrow G(X)$ lying in \mathcal{D} for every $X \in \mathcal{C}$ so that for any map $f : X \rightarrow Y$, we have a commutative diagram

$$\begin{array}{ccc} F(X) & \xrightarrow{\eta_X} & G(X) \\ F(f) \downarrow & & \downarrow G(f) \\ F(Y) & \xrightarrow{\eta_Y} & G(Y) \end{array}$$

Definition 5.8.2 (Homology theory). A *homology theory* is a sequence of [functors](#)

$$H_n : \text{pairs } (X, A) \text{ of spaces} \rightarrow \text{Abelian groups}$$

equipped with [natural transformations](#) $\partial : H_n(X, A) \rightarrow H_{n-1}(A)$, where $H_{n-1}(A) := H_{n-1}(A, \emptyset)$, is called the boundary map.

Naturality here means that for any map $f : (X, A) \rightarrow (Y, B)$ we have a commutative diagram

$$\begin{array}{ccc} H_n(X, A) & \xrightarrow{\partial} & H_{n-1}(A) \\ f_* \downarrow & & \downarrow f_* \\ H_n(Y, B) & \xrightarrow{\partial} & H_{n-1}(B) \end{array}$$

These must satisfy the following 5 axioms.

- (1) (Homotopy) If $f, g : (X, A) \rightarrow (Y, B)$ and $f \simeq g$, then $f_* = g_*$.

(2) (Excision) If $U \subseteq A \subseteq X$ such that $\overline{U} \subseteq \text{Int}(A)$, then

$$\iota: (X \setminus U, A \setminus U) \hookrightarrow (X, A)$$

induces isomorphisms on H_n .

(3) (Dimension) $H_n(*) = 0$ for all $n \neq 0$.

(4) (Additivity) $H_n(\coprod_{\alpha} X_{\alpha}) = \bigoplus_{\alpha} H_n(X_{\alpha})$.

(5) (Exactness) If we have an inclusion $\iota: A \hookrightarrow X^a$ and $j: X \rightarrow (X, A)$ induces a long **exact sequence**

$$\dots \rightarrow H_n(A) \xrightarrow{\iota_*} H_n(X) \xrightarrow{j_*} H_n(X, A) \xrightarrow{\partial} H_{n-1}(A) \rightarrow \dots$$

^aNote that we use $X := (X, \emptyset)$ for every space X .

Definition 5.8.3 (Extraordinary homology theory). If H_* satisfies all **axioms** but dimension, it is called an *extraordinary homology theory*.

Example. Topological K -theory, bordism, and cobordism.^a

^a<https://en.wikipedia.org/wiki/Cobordism>

Theorem 5.8.1. If $H_n: \text{CW pairs} \rightarrow \underline{\text{Ab}}$ is a **homology theory** and $H_0(*) = \mathbb{Z}$, then H_n are exactly the **singular homology functors** up to a natural isomorphism of **functors**.

More generally, if $H_0(*) = G$, then H_n are exactly the **singular homology functors** with coefficients in the **Abelian group** G .

Proof. Given H_* , reconstruct the **cellular chain groups** $H_n(X^n, X^{n-1})$ using the **axioms**.

- Show the **homology** of this **chain complex** are the **cellular homology groups** of X .
- Show these agree with $H_n(X^n, X^{n-1})$. The exact same argument in **Theorem 5.7.2** applies.

We then check that the **cellular homology groups** we just constructed satisfies the **degree formula** as in our last step. This is a bit more difficult, but we won't get into it. ■

Chapter 6

Lefschetz Fixed Point Theorem

After developing [homology theory](#) rigorously, we now see an incredibly useful and interesting application and some of its implication as well.

6.1 Trace

Definition 6.1.1 (Trace). Let $\varphi: \mathbb{Z}^n \rightarrow \mathbb{Z}^n$ be a group homomorphism, we may represent this with a matrix $A = [a_{ij}]_{i,j}$ with *trace* being

$$\text{tr}(A) := a_{11} + \dots + a_{nn}.$$

For a group homomorphism $\varphi: M \rightarrow M$ where M is a [finitely generated Abelian group](#), we define the *trace* of φ to be the *trace* of the induced map $\bar{\varphi}: M/M_T \rightarrow M/M_T$, where M_T is the [torsion subgroup](#) of M .

Exercise. We have

(1) $\text{tr}(AB) = \text{tr}(BA)$.

(2) $\text{tr}(A) = \text{tr}(BAB^{-1})$.

Thus, [trace](#) is independent of change of basis of \mathbb{Z}^n .

Lecture 36: Lefschetz Fixed Point Theorem

6.2 Lefschetz Fixed Point Theorem

6 Apr. 10:00

Definition 6.2.1 (Lefschetz number). Let X be a space with the assumption that $\bigoplus_k H_k(X)$ is finitely generated.^a Then the *Lefschetz number* $\tau(f)$ of a map $f: X \rightarrow X$ is

$$\tau(f) := \sum_k (-1)^k \text{tr}(f_*: H_k(X) \rightarrow H_k(X)).$$

^aThat is, each [homology group](#) is finitely generated, and there are finitely many nonzero [homology groups](#). For example X could be a finite [CW complex](#).

Remark. In particular, we can also write

$$\text{tr}(f_* \circ H_k(X)).$$

Example (Euler characteristic via homology). When $f \simeq \text{id}_X$, we have $f_* = \text{id}_{H_k(X)}$ for all k . Then

$$\text{tr}(f_* : H_k(X) \rightarrow H_k(X)) = \text{rank}(H_k(X)).$$

Hence, we further have

$$\tau(f) = \sum_k (-1)^k \text{rank}(H_k(X)) =: \chi(X),$$

where $\chi(X)$ is the *Euler characteristic*.

This is not what we would use typically. Traditionally, we have the following.

Definition 6.2.2 (Euler characteristic). Let X be a finite **CW complex**, then the *Euler characteristic* $\chi(X)$ of x is defined by the alternating sum

$$\chi(X) = \sum_n (-1)^n c_n$$

where c_n is the number of **n -cells** of X .

Proposition 6.2.1. Definition 6.2.2 and the definition given in this example coincides

Proof. This is immediately by the fact that the **homology group** can be calculated by **cellular homology**, hence c_n is just $\text{rank}(H_n(X))$ for all n , so the result follows. ■

Theorem 6.2.1 (Lefschetz Fixed Point Theorem). Suppose X admits a finite triangulation,^a or more generally, X is a **retract** of a finite **simplicial complex**. If $f : X \rightarrow X$ is a map with $\tau(f) \neq 0$, then f has a fixed point.

^ai.e. a finite **simplicial complex** structure.

Note. Note that the converse does not hold. And in particular, we have

$$\tau(f) = \sum_k \text{tr}(f_{\#} \circ C_k^{\text{CW}}(X)).$$

Theorem 6.2.2. If X is a compact, locally **contractible** space that can be embedded in \mathbb{R}^n for some n , then X is a **retract** of a finite **simplicial complex**.

Remark. This includes

- Compact Manifolds.
- Finite **CW complexes**.

Hence, we see that **Theorem 6.2.1** applies on compact manifolds and finite **CW complexes** in particular.

Definition 6.2.3. Let \mathbb{F} be a field, and let $H_k(X; \mathbb{F})$ be the k -th homology of X with coefficients in \mathbb{F} . Then $H_k(X; \mathbb{F})$ is always a vector space over \mathbb{F} . Define $\tau^{\mathbb{F}}(X)$ be

$$\sum_k (-1)^k \text{tr}(f_* : H_k(X; \mathbb{F}) \rightarrow H_k(X; \mathbb{F})).$$

Remark. The **Lefschetz fixed point theorem** still holds if we replace $\tau(X) \neq 0$ with $\tau^{\mathbb{F}}(X) \neq 0$.

Lecture 37: Simplicial Approximation

8 Apr. 10:00

Example. Let $f: S^n \rightarrow S^n$ be a [degree](#) d map. Then $\tau(f)$ is

$$(-1)^0 \operatorname{tr}(f_*: H_0(S^n) \rightarrow H_0(S^n)) + (-1)^n \operatorname{tr}(f_*: H_n(S^n) \rightarrow H_n(S^n)).$$

Since $f_*: H_0(S^n) \rightarrow H_0(S^n)$ is the identity, and $f_*: H_n(S^n) \rightarrow H_n(S^n)$ is given by the 1×1 matrix with entry d . And then we have

$$\tau(f) = 1 + (-1)^n d.$$

Corollary 6.2.1. $f: S^n \rightarrow S^n$ has a fixed point whenever $1 + (-1)^n \neq 0$. Namely, whenever $d \neq (-1)^{n+1}$. That is f has a fixed point if its [degree](#) is not equal to the [degree](#) of the antipodal map.

Exercise. If $f: X \rightarrow X$, then $\operatorname{tr}(f_*: H_0(X) \rightarrow H_0(X))$ is equal to the number of [path](#)-components of X mapped to themselves.

Exercise. If X is [contractible](#), then for $f: X \rightarrow X$, $\tau(f) = 1$.

Answer. Since the [homology](#) of f is concentrated in [degree](#) zero, the result follows. \circledast

Exercise. If X is a [contractible](#) compact manifold or finite [CW complex](#), every $f: X \rightarrow X$ has a fixed point.

Answer. From the last exercise, we have $\tau(f) = 1$. And since we have compactness, by [Theorem 6.2.1](#), the result follows.

Remark. In particular, this recovers [Brouwer's Fixed Point Theorem](#). \circledast

Example. If we consider the map $f: \mathbb{R} \rightarrow \mathbb{R}$ given by translation by $x \neq 0$, then $\tau(f) = 1$, but f does not have a fixed point.

Proof. The key here is that \mathbb{R} is not compact. \circledast

Example (QR May 2016). Let X be a finite, connected [CW complex](#). \tilde{X} is its [universal cover](#), and \tilde{X} is compact. Show that \tilde{X} cannot be [contractible](#) unless X is [contractible](#).

Proof. We actually have two different approaches.

1. By homework, we then know that, since \tilde{X} is [contractible](#) and \tilde{X} has finitely many sheets d over X ,

$$1 = \chi(\tilde{X}) = d \cdot \chi(X).$$

Therefore, $\chi(X) = d = 1$, and so $p: \tilde{X} \rightarrow X$ is a 1-sheeted [cover](#), so it is a homeomorphism. Therefore, X is [contractible](#).

2. Since \tilde{X} is [contractible](#), $\tau(f) = 1$ for all $f: \tilde{X} \rightarrow \tilde{X}$. Furthermore, because \tilde{X} is compact and covers a finite [CW complex](#), it is a finite [CW complex](#). Therefore, the [Lefschetz fixed point theorem](#) applies, so any such map has a fixed point. If f is a [deck map](#), then that means that $f = \operatorname{id}_{\tilde{X}}$ from [Corollary 4.2.1](#).

We have proved then that $X \cong \tilde{X} / G(\tilde{X})$ because $p: \tilde{X} \rightarrow X$ is [normal](#), but then the [deck](#)

group $G(\tilde{X})$ is trivial, so $X \cong \tilde{X}$, and we are done.

⊛

Exercise. A 1-sheeted [cover](#) is always injective and surjective. Furthermore, it's a local homeomorphism. This suffices to show that a 1-sheeted cover is a homeomorphism.

Theorem 6.2.3. If X is a finite [CW complex](#), with [cellular chain groups](#) $H_n(X^n, X^{n-1})$. If we have a cellular map $f: X \rightarrow X$, so f induces maps $f_*: H_n(X^n, X^{n-1}) \rightarrow H_n(X^n, X^{n-1})$. Then

$$\tau(f) = \sum_n (-1)^n \operatorname{tr}(f_*: H_n(X^n, X^{n-1}) \rightarrow H_n(X^n, X^{n-1})).$$

Proof. Do some algebra! This is a purely algebraic fact

Exercise. Given a commutative diagram with [exact](#) rows

$$\begin{array}{ccccccc} 0 & \longrightarrow & A & \longrightarrow & B & \longrightarrow & C \longrightarrow 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma \\ 0 & \longrightarrow & A' & \longrightarrow & B' & \longrightarrow & C' \longrightarrow 0 \end{array}$$

then $\operatorname{tr}(\beta) = \operatorname{tr}(\alpha) + \operatorname{tr}(\gamma)$.

Using the above result, the theorem follows by an argument analogous to the argument for Euler Characteristic in Homework. ■

6.3 Simplicial Approximation Theorem

As previously seen. Recall the definition of [simplicial complex](#).

Definition 6.3.1 (Simplicial map). A *simplicial map* $f: K \rightarrow L$ is a continuous map that sends each [simplex](#) of K to a (possibly smaller dimensional) [simplex](#) of L by a linear map in the form of

$$\sum t_i v_i \mapsto \sum t_i f(v_i).$$

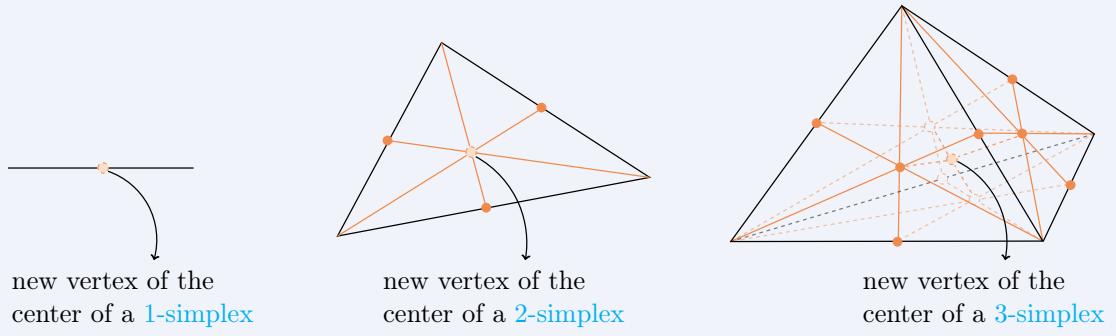
Remark. A [simplicial map](#) is completely determined by its restriction to the vertex set.

Lecture 38: Simplicial Approximation

Theorem 6.3.1 (Simplicial approximation theorem). Given any continuous map $f: K \rightarrow L$ where K is a finite [simplicial complex](#) and L is any [simplicial complex](#). Then f is [homotopic](#) to a map that is [simplicial](#) with respect to some iterated [Barycentric subdivision](#) of K .

11 Apr. 10:00

Example (Barycentric subdivision). Here is barycentric subdivision in pictures.



That is, we add a new vertex to the center of every **subsimplex**, filling things in like the above.

Note. This means that when we go one dimensional higher, the new vertex added in each **subsimplex** carrying through to the next dimension as well.

For an n -simplex we end up with $(n + 1)!$ -simplices with replace it.

6.4 Proof of Lefschetz Fixed Point Theorem

We now have enough tools to prove [Theorem 6.2.1](#)

Proof Outline of Theorem 6.2.1. Fix a space X which is a finite **simplicial complex** (or a **retract** of a finite **simplicial complex**) and a map $f: X \rightarrow X$.

Then we proceed step by step.

- (1) We first reduce to the case of a finite **simplicial complex** X . Suppose K is a finite **simplicial complex**, with $r: K \rightarrow X$ a **retraction**. First notice that the following composite of maps

$$K \xrightarrow{r} X \xrightarrow{f} X \xrightarrow{\iota} K$$

has the same fixed points as f .

Exercise. $r_*: H_n(K) \rightarrow H_n(X)$ is split surjective,^a and so it has to be a projection onto a direct summand.

^aSee ι_* .

Exercise. It follows that $\text{tr}(\iota_* \circ f_* \circ r_* \circ \iota) = \text{tr}(f_*)$ on k^{th} **homology**.

This implies that $\tau(f) = \tau(\iota \circ f \circ r)$, therefore if we can prove the result for a finite **simplicial complex** then we are done.

- (2) Let X be a finite **simplicial complex**. We show that if $f: X \rightarrow X$ has no fixed points, then $\tau(f) = 0$.

The goal now is to find **subdivisions** K, L of X and $g: K \rightarrow L$ so that

- g is **simplicial**.
- $g \simeq f$, $\tau(f) = \tau(g)$.
- $g(\sigma) \cap \sigma = \emptyset$ for all **simplices** σ .

Note. i.e., it moves every σ .

So this becomes a few steps, none of which we'll justify too formally. Firstly, since [trace](#) is given by diagonal entries of g in a matrix which respects to basis of [simplices](#) of K and L , if g fixes no basis entries, then it has [trace](#) 0. With this, we have the following steps.

- Choose a metric d on X .
- Since X is compact, and f has no fixed point, then $d(x, f(x))$ has some minimum value $\epsilon > 0$.
- Subdivide all [simplices](#) of X until [simplices](#) have diameter smaller than $\epsilon/100$.^b Call this [subdivision](#) L .
- Use the [simplicial approximation theorem](#) to obtain a map $g: K \rightarrow L$, where K is a [subdivision](#) of L and $g \simeq f$.
- By the proof^c of [simplicial approximation theorem](#), we can construct g so that for all [simplices](#) σ , $g(\sigma)$ is not too far from $f(\sigma)$. We can then conclude that $g(\sigma) \cap \sigma = \emptyset$.
- Consider $g_{\#} \circ C_*^{CW}(K)$, so then g is a cellular map $K \rightarrow K$ that moves every [cell](#). We can then check that

$$\tau(f) = \tau(g) = \sum (-1)^n \operatorname{tr} \underbrace{(g_{\#}: \text{cellular } n\text{-chains} \rightarrow \text{cellular } n\text{-chains})}_{g_{\#} \circ C_*^{CW}(K)} = 0$$

Because each g_* has vanishing diagonal entries.

This proves the theorem. ■

^bJust a random constant!

^cWe omit the proof, see Hatcher[HPM02].

Chapter 7

Epilogue

There are some final remarks we would like to make.

Lecture 39: Proof of Seifert-Van-Kampen Theorem

7.1 Proof of Seifert-Van-Kampen Theorem

13 Apr. 10:00

Let's start to prove [Theorem 3.6.1](#) which we omit before.

Proof of Theorem 3.6.1. The outline of the proof is the following. Let $X = \bigcup_{\alpha} A_{\alpha}$ where A_{α} are open, [path](#)-connected and contain the glue-point x_0 . We also must guarantee that $A_{\alpha} \cap A_{\beta}$ is [path](#)-connected.

1. Since we have a map induced by the inclusions

$$\Phi: \ast_{\alpha} \pi_1(A_{\alpha}, x_0) \rightarrow \pi_1(X, x_0).$$

We want to show that Φ is surjective. Take some $\gamma: I \rightarrow X$, then by the compactness of the interval I , we can show that there is a partition I with $s_1 < \dots < s_n$ so that

$$\gamma|_{[s_i, s_{i+1}]} =: \gamma_i$$

has image in A_{α_i} for some α_i .

Exercise. Showing the above fact is a good exercise for point-set topology.

Specifically, since

- A_{α} is open for all α
- I is compact,

then for all i , we choose a [path](#) h_i from x_0 to $\gamma(s_i)$ in $A_{\sigma_{i-1}} \cap A_{\alpha_i}$, using [path](#)-connectedness of the pairwise intersections. Now, take γ and write it as

$$\gamma = (\gamma_1 \cdot \bar{h}_1) \cdot (\bar{h}_1 \cdot \gamma_2) \cdot \dots \cdot (\gamma_{n-1} \cdot \bar{h}_{n-1}) \cdot (h_{n-1} \cdot \gamma_n).$$

Observe that each of these [paths](#) is fully contained in A_{α_i} , so this implies that $\gamma \in \text{Im}(\Phi)$, therefore Φ is surjective.

2. For the next step, we'll show that the second part of [Theorem 3.6.1](#). Assume that our triple intersections are [path](#)-connected. We want to show that $\ker(\Phi)$ is generated by

$$(i_{\alpha\beta})_*(\omega)(i_{\beta\alpha})_*(\omega)^{-1},$$

where $i_{\alpha\beta}: A_\alpha \cap A_\beta \hookrightarrow A_\alpha$ for all loops $\omega \in \pi_1(A_\alpha \cap A_\beta, x_0)$.

Before we go further, we'll need a specific definition.

Definition 7.1.1 (Factorization). A *factorization* of a [homotopy](#) class $[f] \in \pi_1(X, x_0)$ is a formal product

$$[f_1][f_2] \cdots [f_\ell]$$

with $[f_i] \in \pi_1(A_\alpha, x_0)$ such that

$$f \simeq f_1 \cdot f_2 \cdots f_\ell.$$

We showed that every $[f]$ has a [factorization](#) in step 1 already. Now we want to show that two [factorizations](#)

$$[f_1] \cdots [f_\ell] \text{ and } [f'_1] \cdots [f'_{\ell'}]$$

of $[f]$ must be related by two moves:

- (1) $[f_i] \cdot [f_{i+1}] = [f_i \cdot f_{i+1}]$ if $[f_i], [f_{i+1}] \in \pi_1(A_\alpha, x_0)$. Namely, the reaction defining the [free product](#) of groups.
- (2) $[f_i]$ can be viewed as an element of $\pi_1(A_\alpha, x_0)$ or $\pi_1(A_\beta, x_0)$ whenever

$$[f_i] \in \pi_1(A_\alpha \cap A_\beta, x_0).$$

This is the relation defining the [amalgamated free product](#).

Now, let $F_t: I \times I \rightarrow X$ be a [homotopy](#) from $f_1 \cdots f_\ell$ to $f'_1 \cdots f'_{\ell'}$, since they both represent $[f]$. We subdivide $I \times I$ into rectangles R_{ij} so that

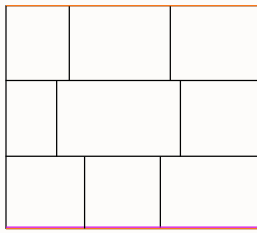
$$F(R_{ij}) \subseteq A_{\alpha_{ij}} =: A_{ij}$$

for some α_{ij} using compactness. We also argue that we can perturb the corners of the squares so that a corner lies only in three of the A_α 's indexed by adjacent rectangles.

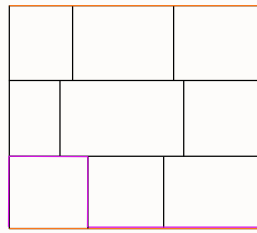
A_{31}	A_{32}	A_{33}
A_{21}	A_{22}	A_{23}
A_{11}	A_{12}	A_{13}

We also argue that we can set up our subdivision so that the partition of the top and bottom intervals must correspond with the two [factorizations](#) of $[f]$. We then perform our [homotopy](#) one rectangle at a time.

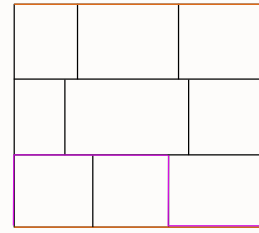
ending loop $f'_1 \cdot \dots \cdot f'_{\ell'}$



starting loop $f_1 \cdot \dots \cdot f_{\ell}$



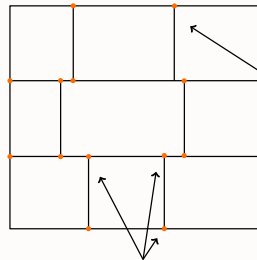
step 1



step 2

Idea: Argue that **homotoping** over a single rectangle has the effect of using allowable moves to modify the **factorization**.

At each triple intersection, choose a **path** from f (corner) to x_0 which lies in the triple intersection, so we use the assumption that the triple intersections are **path**-connected.



In each intersection, choose a **path** from f (corner) to x_0

Choose **path** h from image of this corner to x_0

Along the top and bottom, we make choices compatible with the two **factorizations**. It's now an exercise to check that these choices result in **homotoping** across a rectangle gives a new **factorization** related by an allowable move.

■

Lecture 40: Prepare for Final

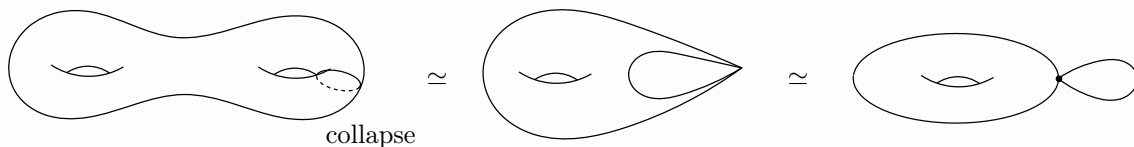
7.2 Review Problems

15 Apr. 10:00

We now go through some problems to get prepared for the final!

Exercise (QR May 2019). $T = S^1 \times S^1$, $T' = T / S \times \{1\}$. Find H_* , π_1 of $T \# T'$ (connected sum).

Answer. We see that



We then see that $T \# T'$ is a **wedge** of T and S^1 , hence the fundamental group is just $\mathbb{Z}^2 * \mathbb{Z}$, where \mathbb{Z}^2 is from T and \mathbb{Z} is from S^1 . \circledast

Exercise (QR Aug. 2019). Let X be a **CW complex** obtain from a k -sphere, $k \geq 1$, by attaching two $(k+1)$ -cells along **attaching maps** of deg m, n . Calculate $H_*(X)$.

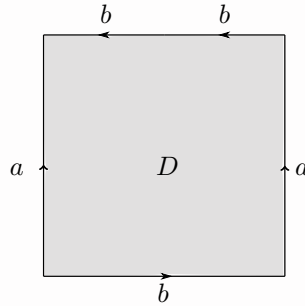
Answer. We use **cellular homology**. Specifically, we have the following.

$$\begin{array}{ccc} \mathbb{Z}^2 = C_{k+1} & \xrightarrow{\partial_{k+1}} & \mathbb{Z} = C_k \\ (1, 0) & \longmapsto & m \\ (0, 1) & \longmapsto & n \end{array}$$

Hence, we see that $\ker(\partial_{k+1}) \cong \mathbb{Z}$, and $\text{Im}(\partial_{k+1}) = \gcd(m, n)\mathbb{Z}$. *

Exercise (QR May 2017). Let S^1 be the complex numbers of absolute value 1 with induced topology. Let K be the quotient of $S^1 \times [0, 1]$ by identifying $(z, 0)$ with $(z^{-2}, 1)$. Compute $H_*(K)$.

Answer. Again, we use **cellular homology**. We use the following gluing instruction.



*

Exercise (QR Sep. 2016). Let $Z = \{(x, y) \in \mathbb{C}^2 \mid x = 0 \text{ or } y = 0\}$. Find $H_*(\mathbb{C}^2 \setminus Z)$.

Answer. We see that

$$(\mathbb{C} \setminus \{0\}) \times (\mathbb{C} \setminus \{0\}) \simeq S^1 \times S^1,$$

which is a torus. *

Exercise (QR May 2017). Let X be the connected **CW complex**, $H_i(X) = 0$ for all $i > 0$. Prove that

$$H_n(X \times S^k) = \begin{cases} \mathbb{Z}, & \text{if } n = 0; \\ 0, & \text{otherwise.} \end{cases}$$

Answer. We can induct on k and use Mayer-Vietoris long sequence. Let $U = X \times$ upper hemisphere, $V = X \times$ lower hemisphere, then we have

$$U \simeq X, \quad V \simeq X,$$

and hence $U \cap V \simeq X \times S^{k-1}$. *

Lecture 41: Prepare for Final

We now go through more problems to get prepared for the final!

18 Apr. 10:00

Exercise (QR Jan. 2021). Let G be a connected topological space and \bar{w} a topological group structure, i.e., continuous multiplication $M: G \times G \rightarrow G$ and inverse $i: G \rightarrow G$ that define a group structure. Assume G has finite CW complex structure. Show $\chi(G) = 0$ unless $G = \{1\}$.

Answer. Let $g \in G$ such that $g \neq \text{id}$. We can then choose a path γ from g to id . Then we have

$$\begin{aligned}\tau_g: G &\rightarrow G \\ h &\mapsto gh.\end{aligned}$$

Then γ gives homotopy from τ_g to id such that $h \mapsto \gamma(t)h$, so

$$\tau(\tau_g) = \tau(\text{id}) = \chi(G) = 0,$$

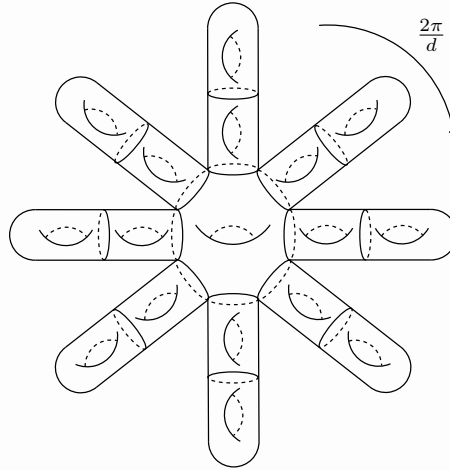
hence by Theorem 6.2.1, τ_g has no fixed points. *

Exercise (QR May 2019). For what $g \geq 0$ is it true that for all $h \geq g$, a compact oriented genus- g surface X (no boundary) has covering $f: Y \rightarrow X$ where Y is a compact, oriented surface of genus- h ?

Answer. From Euler characteristic, we have

$$(2 - 2g)d = 2 - 2h$$

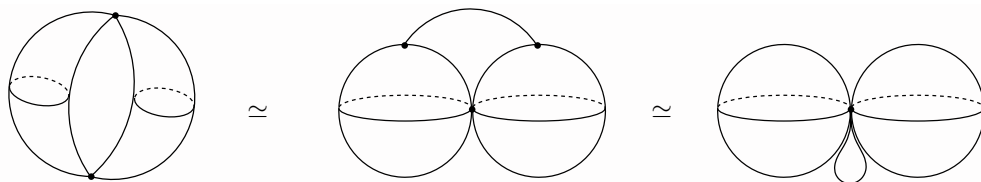
for a degree d covering. This implies $h \equiv 1 \pmod{g-1}$. We see that the only solutions for all h if $g = 2$. Then for a particular d , we have the following cover.



*

Exercise (QR Jan. 2019). Let S_1, S_2 be two disjoint copies of n -sphere, $n > 1$. Choose distinct points $A_i, B_i \in S_i$, and let Z is obtained by gluing $A_1 \sim A_2, B_1 \sim B_2$. What's the lowest number of cells in CW complex structure on Z .

Answer. In $n = 2$, we have the following figure.



⊛

Exercise (QR Jan. 2016). Let $U, V \subseteq S^n$, $n \geq 2$ be non-empty connected open sets such that $S^n = U \cup V$. Show $U \cap V$ is connected.

Answer. We simply calculate \tilde{H}_0 via Mayer-Vietoris.

⊛

Exercise (QR Jan. 2016). Let p be a prime, and X be a finite CW complex, $\mathbb{Z}/p\mathbb{Z} \curvearrowright X$.

- (a) If $\chi(X)$ is not divisible by p , show that the action has a (global) fixed point.
- (b) Give an example of such an action that is fixed point free when $\chi(X) = 0$.

Answer. We have the following.

- (a) We use the Euler characteristic on the covering space action.^a
- (b) Rotation $2\pi/p$ on S^1 .

⊛

^aSince we assume has no fixed point, with the fact that X admits a CW complex structure hence Hausdorff, so $\mathbb{Z}/p\mathbb{Z}$ is indeed a covering space action.

Appendix

Appendix A

Additional Proofs

A.1 Seifert-Van Kampen Theorem on Groupoid

Theorem A.1.1 (Seifert-Van Kampen Theorem on groupoid). Given X_0, X_1, X as topological spaces with $X_0 \cup X_1 = X$. Then the functor $\Pi: \underline{\text{Top}} \rightarrow \underline{\text{Gpd}}$ maps the [cocartesian](#) diagram in $\underline{\text{Top}}_*$ to a [cocartesian](#) diagram in $\underline{\text{Gp}}$ as follows.

$$\begin{array}{ccccc} (X_0 \cap X_1, x_0) & \xrightarrow{j_0} & (X_0, x_0) & & \Pi(X_0 \cap X_1) \xrightarrow{\Pi(j_0)} \Pi(X_0) \\ j_1 \downarrow & & \downarrow i_0 & \xrightarrow{\Pi} & \Pi(j_1) \downarrow \quad \quad \downarrow \Pi(i_0) \\ (X_1, x_0) & \xrightarrow{i_1} & (X, x_0) & & \Pi(X_1) \xrightarrow{\Pi(i_1)} \Pi(X) \end{array}$$

Note. Notice that X_0, X_1, X don't need to be [path](#)-connected in particular.

Surprisingly, the proof of [Appendix A.1](#) is much more elegant with the elementary proof of [Theorem 3.6.1](#), hence we give the proof here.

Proof. Let $\mathcal{G} \in \text{Ob}(\underline{\text{Gpd}})$ a [groupoid](#), and given [functors](#)

$$F: \Pi(X_0) \rightarrow \mathcal{G}, \quad G: \Pi(X_1) \rightarrow \mathcal{G}$$

such that

$$\begin{array}{ccc} \Pi(X_0 \cap X_1) & \xrightarrow{\Pi(j_0)} & \Pi(X_0) \\ \Pi(j_1) \downarrow & & \downarrow \Pi(i_0) \\ \Pi(X_1) & \xrightarrow{\Pi(i_1)} & \Pi(X) \end{array} \quad \begin{array}{c} \xrightarrow{F} \\ \text{---} \exists! K \text{---} \\ \xrightarrow{G} \end{array} \mathcal{G}$$

We now only need to prove that there exists a unique [functor](#) $K: \Pi(X) \rightarrow \mathcal{G}$ such that the above diagram commutes.

We can define K as

- on [objects](#): For all $x \in \text{Ob}(\Pi(X)) = X$,

$$K(x) = \begin{cases} F(x), & \text{if } x \in X_0; \\ G(x), & \text{if } x \in X_1. \end{cases}$$

This is well-defined since the diagram (without K) commutes.

- on **morphisms**: For every $p, q \in X$, $\langle \gamma \rangle : p \rightarrow q$ in $\text{Hom}_{\Pi(X)}(p, q)$, we need to define $K(\langle \gamma \rangle) \in \text{Hom}_{\mathcal{G}}(K(p), K(q))$. Our strategy is for every path γ from p to q , we define $\tilde{K}(\gamma) \in \text{Hom}_{\mathcal{G}}(K(p), K(q))$. Then if we also have $\tilde{K}(\gamma) = \tilde{K}(\gamma')$ for $\gamma \simeq \gamma' \text{ rel}\{0, 1\}$, then we can just let

$$K(\langle \gamma \rangle) := \tilde{K}(\gamma).$$

Now we start to construct \tilde{K} .

Given a path $\gamma : [0, 1] \rightarrow X$, $\gamma(0) = p, \gamma(1) = q$. Since $\text{Int}(X_0) \cup \text{Int}(X_1) = X$, we see that

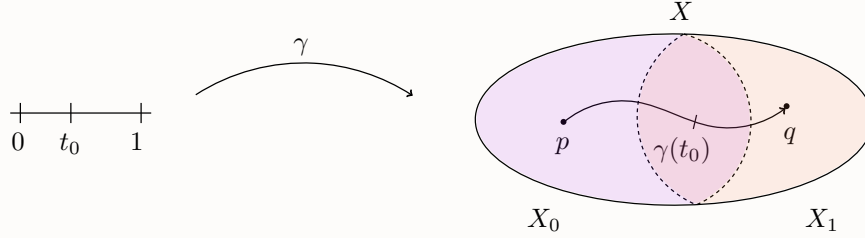
$$\gamma^{-1}(\text{Int}(X_0)) \cup \gamma^{-1}(\text{Int}(X_1)) = [0, 1].$$

From Lebesgue Lemma^a, there exists a finite partition

$$0 = t_0 < t_1 < \dots < t_{m-1} < t_m = 1$$

such that for every i ,

$$\gamma([t_{i-1}, t_i]) \subset \text{Int}(X_0) \text{ or } \text{Int}(X_1).$$



Now, let $\gamma_i : [0, 1] \rightarrow X, t \mapsto \gamma((1-t)t_{i-1} + t \cdot t_i)$, we see that γ_i is either a **path** in X_0 or X_1 . We then define $\tilde{K}(\gamma) := \tilde{K}(\gamma_m) \circ \tilde{K}(\gamma_{m-1}) \circ \dots \circ \tilde{K}(\gamma_1) \in \text{Hom}_{\mathcal{G}}(K(P), K(q))$ such that

$$\tilde{K}(\gamma_i) = \begin{cases} F(\langle \gamma_i \rangle), & \text{if } \gamma_i \subset X_0; \\ G(\langle \gamma_i \rangle), & \text{if } \gamma_i \subset X_1. \end{cases}$$

We need to prove that $\tilde{K}(\gamma)$ does not depend on the partition. It's sufficient to prove that for any partition

$$0 = t_0 < t_1 < \dots < t_{m-1} < t_m = 1,$$

we consider any **finer** partition

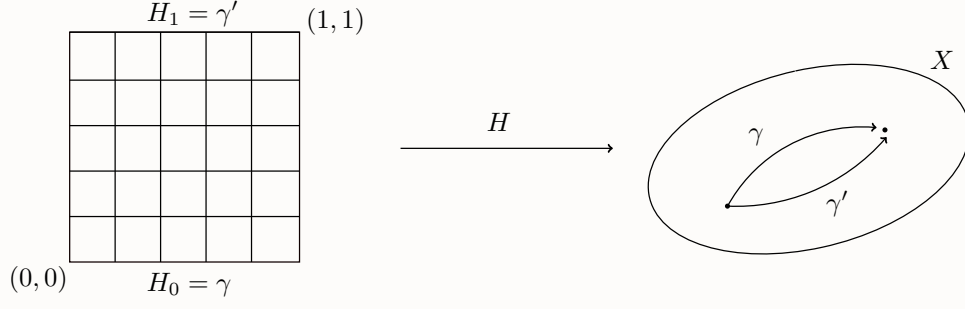
$$0 = t_0 = t_{10} < t_{11} < \dots < t_{1K_1} = t_1 = t_{20} < t_{21} < \dots < t_{mK_m} = t_m = 1.$$

As before, we denote $\gamma_{ij} : [0, 1] \rightarrow X, t \mapsto \gamma((1-t)t_{ij-1} + t \cdot t_{ij})$. It's clear that as long as

$$\tilde{K}(\gamma_i) = \tilde{K}(\gamma_{iK_i}) \circ \tilde{K}(\gamma_{iK_i-1}) \circ \dots \circ \tilde{K}(\gamma_{i0}),$$

then our claim is proved. But this is immediate since F and G are **functor** and for any i , we only use either F or G all the time.

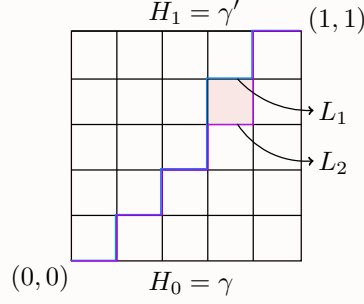
Now we prove $\gamma \simeq \gamma' \text{ rel}\{0, 1\}$, then $\tilde{K}(\gamma) = \tilde{K}(\gamma')$. This is best shown by some diagram.



The left-hand side represents a partition \mathcal{P} of $[0, 1] \times [0, 1]$ such that every small square's image in X under H is either entirely in X_0 or in x_1 . Consider all paths from $(0, 0)$ to $(1, 1)$ such that it only goes right or up. We see that for any such path L , consider

$$\gamma_L: [0, 1] \rightarrow L, \quad t \mapsto \gamma_L(t).$$

We let $\Gamma_L: H|_L \circ \gamma_L: [0, 1] \rightarrow X$, we see that Γ_L is a **path** from p to q . Now, if for two paths L_1 and L_2 such that they only differ from a square.



We claim that $\gamma_{L_1}, \gamma_{L_2}$ are two **paths** from p to q , and $\tilde{K}(\Gamma_{L_1}) = \tilde{K}(\Gamma_{L_2})$. Now, we denote Γ_0 and Γ_1 as follows.

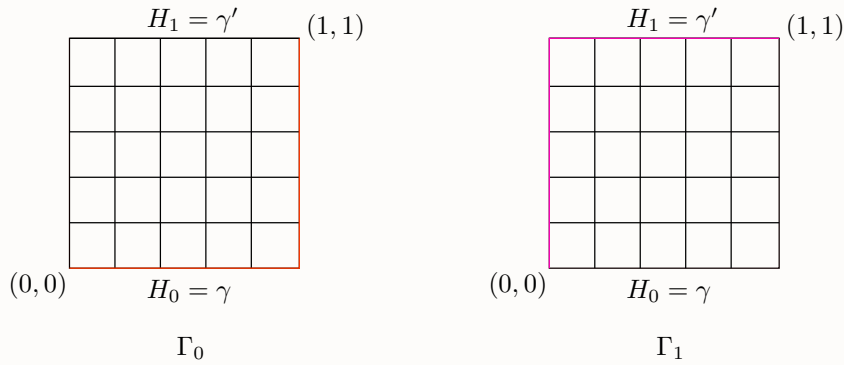


Figure A.1: The definition of Γ_0 and Γ_1 .

It's clearly that by only finitely many steps, we can transform Γ_0 to Γ_1 , hence

$$\tilde{K}(\Gamma_0) = \tilde{K}(\Gamma_1).$$

Finally, we observe that

$$\tilde{K}(\gamma_0) = \tilde{K}(\Gamma_0) = \tilde{K}(\Gamma_1) = \tilde{K}(\gamma_1).$$

If we now define $K(\langle \gamma \rangle) = \tilde{K}(\gamma)$, then $K: \text{Mor}(\Pi(X)) \rightarrow \text{Mor}(\mathcal{G})$, then it's well-defined.

We now prove $K: \Pi(X) \rightarrow \mathcal{G}$ is indeed a **functor**. But this is immediate from the definition of K , namely it'll send identity to identity and the composition associates.

Also, we need to prove that the following diagram commutes.

$$\begin{array}{ccc} \Pi(X_0 \cap X_1) & \xrightarrow{\Pi(j_0)} & \Pi(X_0) \\ \Pi(j_1) \downarrow & & \downarrow \Pi(i_0) \\ \Pi(X_1) & \xrightarrow{\Pi(i_1)} & \Pi(X) \end{array} \quad \begin{array}{c} \searrow F \\ \downarrow K \\ \searrow G \end{array} \quad \mathcal{G}$$

But this is again trivial.

Finally, we need to show that such K is unique. This is the same as the proof of [Lemma 2.2.1](#), hence the proof is done. \blacksquare

^ahttps://en.wikipedia.org/wiki/Lebesgue%27s_number_lemma

A.2 An alternative proof of **Seifert Van-Kampen Theorem**

Theorem A.2.1. We claim that the diagram

$$\begin{array}{ccc} \pi_1(X_0 \cap X_1, x_0) & \xrightarrow{(j_0)_*} & \pi_1(X_0, x_0) \\ (j_1)_* \downarrow & & \downarrow (i_0)_* \\ \pi_1(X_1, x_0) & \xrightarrow{(i_1)_*} & \pi_1(X, x_0) \end{array}$$

is **cocartesian**.

Proof. The basic idea is that, for this diagram,

$$\begin{array}{ccc} \Pi(X_0 \cap X_1) & \longrightarrow & \Pi(X_0) \\ \downarrow & & \downarrow \\ \Pi(X_1) & \longrightarrow & \Pi(X) \end{array}$$

we want to construct a **morphism** $r: \Pi(Z) \rightarrow \pi_1(Z, p)$ in $\underline{\text{Gpd}}$ such that $Z = X_0 \cap X_1, X_0, X_1, X$. For every $x \in Z$, we fix a **path** γ_x such that it connects p and x and satisfies

- (1) If $x \in X_0 \cap X_1$, then $\text{Im}(\gamma_x) \subset X_0 \cap X_1$
- (2) If $x \in X_0$, then $\text{Im}(\gamma_x) \subset X_0$
- (3) If $x \in X_1$, then $\text{Im}(\gamma_x) \subset X_1$
- (4) $\gamma_p = c_p$

The proof is given in https://www.bilibili.com/video/BV1P7411N7fW?p=38&spm_id_from=pageDriver. \blacksquare

If have time.

A.3 Cellular Boundary Formula in Definition 5.7.1

Theorem A.3.1. For $n > 1$, the boundary maps ∂_n of cellular chain complex given by

$$\partial_n(e_\alpha^n) = \sum_{\beta} \partial_{\alpha\beta} e_\beta^{n-1}$$

is well-defined.

Proof. Here we are identifying the cells e_α^n and e_β^{n-1} with generators of the corresponding summands of the cellular chain groups, namely $C_n(X)$. The summation in the formula contains only finitely many terms since the attaching map of e_α^n has compact image, so this image meets only finitely many cells e_β^{n-1} . To derive the cellular boundary formula, consider the following commutative diagram.

$$\begin{array}{ccccc} H_n(D_\alpha^n, \partial D_\alpha^n) & \xrightarrow[\cong]{\partial} & \tilde{H}_{n-1}(\partial D_\alpha^n) & \xrightarrow{\Delta_{\alpha\beta*}} & \tilde{H}_{n-1}(S_\beta^{n-1}) \\ \downarrow \Phi_{\alpha*} & & \downarrow \varphi_{\alpha*} & & \uparrow q_{\beta*} \\ H_n(X^n, X^{n-1}) & \xrightarrow{\partial_n} & \tilde{H}_{n-1}(X^{n-1}) & \xrightarrow{q*} & \tilde{H}_{n-1}(X^{n-1} / X^{n-2}) \\ & \searrow d_n & \downarrow j_{n-1} & & \downarrow \cong \\ & & H_{n-1}(X^{n-1}, X^{n-2}) & \xrightarrow{\cong} & H_{n-1}(X^{n-1} / X^{n-2}, X^{n-2} / X^{n-2}) \end{array}$$

where

- Φ_α is the characteristic map of the cell e_α^n and φ_α is its attaching map.
- $q: X^{n-1} \rightarrow X^{n-1} / X^{n-2}$ is the quotient map.
- $q_\beta: X^{n-1} / X^{n-2} \rightarrow S_\beta^{n-1}$ collapses the complement of the cell e_β^{n-1} to a point, the resulting quotient sphere being identified with S_β^{n-1} via the characteristic map Φ_β .
- $\Delta_{\alpha\beta}: \partial D_\alpha^n \rightarrow S_\beta^{n-1}$ is the composition $q_\beta q \varphi_\alpha$, i.e., the attaching map of e_α^n followed by the quotient map $X^{n-1} \rightarrow S_\beta^{n-1}$ collapsing the complement of e_β^{n-1} in X^{n-1} to a point.

The map $\Phi_{\alpha*}$ takes a chosen generator $[D_\alpha^n] \in H_n(D_\alpha^n, \partial D_\alpha^n)$ to a generator of the \mathbb{Z} summand of $H_n(X^n, X^{n-1})$ corresponding to e_α^n . Letting e_α^n denote this generator, commutativity of the left half of the diagram then gives

$$\partial_n(e_\alpha^n) = j_{n-1} \varphi_{\alpha*} \partial[D_\alpha^n].$$

In terms of the basis for $H_{n-1}(X^{n-1}, X^{n-2})$ corresponding to the cells e_β^{n-1} , the map $q_{\beta*}$ is the projection of $\tilde{H}_{n-1}(X^{n-1} / X^{n-2})$ onto its \mathbb{Z} summand corresponding to e_β^{n-1} . Commutativity of the diagram then yields the formula for ∂_n given above. ■

^aWhich is just $D_\beta^{n-1} / \partial D_\beta^{n-1}$.

Appendix B

Algebra

This section aims to give some reference about the required algebra content, including [Abelian groups](#), and [free Abelian group](#), which is used heavily when discuss homology, and also some [homological algebra](#), where we will focus on [exact sequence](#) specifically.

B.1 Abelian Group

Definition B.1.1 (Abelian group). A group (G, \cdot) is an *Abelian group* if for every $a, b \in G$, we have

$$a \cdot b = b \cdot a.$$

We often denote \cdot as $+$ if (G, \cdot) is a [Abelian group](#).

Definition B.1.2 (Product of groups). Given two groups $(G, \cdot), (H, \cdot)$, the *product of G and H* , denoted by $G \times H$ is defined as

$$G \times H = \{(g, h) \mid g \in G, h \in H\}$$

and

$$(g_1, h_1) \cdot (g_2, h_2) := (g_1 \cdot g_2, h_1 \cdot h_2).$$

Notation. For simplicity, given an index set I , we'll denote the order pair $(g_{\alpha_1}, g_{\alpha_2}, \dots)$ as $(g_\alpha)_{\alpha \in I}$. Note that the latter notation can handle the case that I is either countable or uncountable, while the former can only handle the countable case.

Definition B.1.3 (Direct product). Given $(G_\alpha, +)$, $\alpha \in I$ as a collection of [Abelian group](#), we define their *direct product* as

$$\left(\prod_{\alpha \in I} G_\alpha, + \right),$$

where

$$\prod_{\alpha \in I} G_\alpha = \{(g_\alpha)_{\alpha \in I} \mid g_\alpha \in G_\alpha\}$$

and $\forall (g_\alpha), (h_\alpha) \in \prod_{\alpha \in I} G_\alpha$

$$(g_\alpha) + (h_\alpha) := g_\alpha + h_\alpha$$

for all $\alpha \in I$.

Specifically, if I is finite, namely there are only finitely many [Abelian groups](#) $(G_1, +), \dots, (G_n, +)$,

and $\left(\prod_{i=1}^n G_i, +\right)$ can be denoted as

$$(G_1 \times \dots \times G_n, +).$$

Definition B.1.4 (External direct sum). Given a collection of **Abelian groups** $\{G_\alpha\}_{\alpha \in I}$, the *external direct sum* of them, denoted as $(\bigoplus_{\alpha \in I} G_\alpha, +)$ as

$$\bigoplus_{\alpha \in I} G_\alpha := \left\{ (g_\alpha)_{\alpha \in I} \mid \forall_{\alpha \in I} g_\alpha \in G_\alpha, \# \text{ non-zero elements in } g_\alpha < \infty \right\}.$$

And for every $(g_\alpha), (h_\alpha) \in \bigoplus_{\alpha \in I} G_\alpha$,

$$(g_\alpha) + (h_\alpha) := g_\alpha + h_\alpha$$

for all $\alpha \in I$.^a

^aThis may not be the best notation: What we're really trying to say is $(g_\alpha)_{\alpha \in I} + (h_\alpha)_{\alpha \in I} := g_i + h_i$ for all $i \in I$.

Note. We see that

$$\bigoplus_{\alpha \in I} G_\alpha \subset \prod_{\alpha \in I} G_\alpha.$$

Additionally, we also have

$$\left(\bigoplus_{\alpha \in I} G_\alpha, +\right) < \left(\prod_{\alpha \in I} G_\alpha, +\right).$$

Remark. We see that the operation $+$ is indeed closed since the sum of $g, g' \in \bigoplus_{\alpha \in I} G_\alpha$ will have only finitely non-zero elements if g, g' both have only finitely many non-zero elements.

We see that if I is a finite index set, given a collection of **Abelian group** $\{G_\alpha\}_{\alpha \in I}$, then

$$G_1 \times \dots \times G_n = G_1 \oplus \dots \oplus G_n.$$

Definition B.1.5 (Internal direct sum). Given an **Abelian group** G , and a collection of the subgroups $\{G_\alpha\}_{\alpha \in I}$ of G , we say G is an *internal direct sum* of $\{G_\alpha\}_{\alpha \in I}$ if for any $g \in G$, we can write

$$g = \sum_{\alpha \in I} g_\alpha$$

uniquely, where $g_\alpha \in G_\alpha$ has only finitely many non-zero elements. In this case, we denote

$$G = \bigoplus_{\alpha \in I} G_\alpha.$$

Intuitively, the **external direct sum** is to build a new group based on the given collection of groups $\{G_\alpha\}_{\alpha \in I}$, while the internal direct sum is to express an **already known** group G with an **already known** collection of groups $\{G_\alpha\}_{\alpha \in I}$.

Remark (Relation between Internal and External direct sum). Given an **Abelian group** G and its **internal direct sum** decomposition $\bigoplus_{\alpha \in I} G_\alpha$, G is isomorphic to the **external direct sum** of $\{G_\alpha\}_{\alpha \in I}$. We see this from the following group homomorphism:

$$\forall_{g \in G} g = \sum_{\alpha \in I} g_\alpha \mapsto (g_\alpha)_{\alpha \in I}.$$

Conversely, given a collection of **Abelian group** $\{G_\alpha\}_{\alpha \in I}$, and let $G = \bigoplus_{\alpha \in I} G_\alpha$ as the **external**

direct sum of $\{G_\alpha\}$, denote $i_{\alpha_0}: G_{\alpha_0} \rightarrow \bigoplus_{\alpha \in I} G_\alpha$ as a canonical embedding

$$g_{\alpha_0} \mapsto i_{\alpha_0}(g_{\alpha_0}) = (h_\alpha)_{\alpha \in I},$$

where

$$h_\alpha = \begin{cases} g_{\alpha_0}, & \text{if } \alpha_0 = \alpha; \\ 0, & \text{if } \alpha_0 \neq \alpha \end{cases}$$

given α_0 . Then

$$G'_{\alpha_0} := i_{\alpha_0}(G_{\alpha_0}) < \bigoplus_{\alpha \in I} G_\alpha$$

and G is the [internal direct sum](#) of G'_{α_0} , $\alpha_0 \in I$. This is because $\forall g = (g_\alpha)_{\alpha \in I} \in G (= \bigoplus_{\alpha \in I} G_\alpha)$, we have

$$g = \sum_{\alpha \in I} i_\alpha(g_\alpha).$$

Note that the above sum is well-defined since there are only finitely many non-zero elements for each g_α . And additionally, we can see the uniqueness of this decomposition by defining π_{α_0} such that

$$\pi_{\alpha_0}: \bigoplus_{\alpha \in I} G_\alpha \rightarrow G_{\alpha_0}, \quad (g_\alpha)_{\alpha \in I} \mapsto g_{\alpha_0},$$

then $\pi_\alpha \circ i_\alpha = \text{id}_{G_\alpha}$, $\pi_\alpha \circ i_\beta = 0$ for all $\beta \neq \alpha$ and

$$\pi_\beta(g) = \pi_\beta \left(\sum_{\alpha \in I} i_\alpha(g_\alpha) \right) = \sum_{\alpha \in I} \pi_\beta \circ i_\alpha(g_\alpha) = \pi_\beta \circ i_\beta(g_\beta) = g_\beta$$

for all $\beta \in I$, where the second equality is because this summation is finite. Hence, we have

$$g = \sum_{\alpha \in I} i_\alpha(\pi_\alpha(g)).$$

Definition B.1.6. Given two [Abelian groups](#) G, H , we define $\text{Hom}(G, H)$ as

$$\text{Hom}(G, H) := \{f: G \rightarrow H \mid f \text{ is a group homomorphism}\},$$

then we can define

$$\begin{aligned} +: \text{Hom}(G, H) \times \text{Hom}(G, H) &\rightarrow \text{Hom}(G, H) \\ (\varphi, \psi) &\mapsto \varphi + \psi, \end{aligned}$$

where

$$(\varphi + \psi)(g) := \varphi(g) + \psi(g).$$

Remark (Relation between direct sum and direct product). Given a collection of [Abelian groups](#) $\{G_\alpha\}_{\alpha \in I}$, and another [Abelian group](#) H , there exists a φ such that

$$\begin{aligned} \varphi: \text{Hom} \left(\bigoplus_{\alpha \in I} G_\alpha, H \right) &\rightarrow \prod_{\alpha \in I} \text{Hom}(G_\alpha, H) \\ f &\mapsto \varphi(f) := (f_\alpha)_{\alpha \in I} \end{aligned}$$

where $f_\alpha = f \circ i_\alpha$, where i_α is the canonical embedding from G_α to $\bigoplus_{\alpha \in I} G_\alpha$. We claim that φ is an isomorphism.

- φ is injective. This is obvious since $\ker(\varphi) = 0$ from the fact that if $\varphi(f) = 0$, then $f_\alpha = 0$ for all α , hence f is 0.

- φ is surjective. For every $(f_\alpha)_{\alpha \in I} \in \prod_{\alpha \in I} \text{Hom}(G_\alpha, H)$, we define

$$f: \bigoplus_{\alpha \in I} G_\alpha \rightarrow H$$

$$\sum_{\alpha \in I} g_\alpha \mapsto \sum_{\alpha \in I} f_\alpha(g_\alpha).$$

We see that $f \in \text{Hom}(\bigoplus_{\alpha \in I} G_\alpha, H)$ and $\varphi(f) = (f_\alpha)_{\alpha \in I}$.

This shows that

$$\text{Hom}\left(\bigoplus_{\alpha \in I} G_\alpha, H\right) \cong \prod_{\alpha \in I} \text{Hom}(G_\alpha, H).$$

Exercise. We can show that

$$\text{Hom}\left(H, \prod_{\alpha \in I} G_\alpha\right) \cong \prod_{\alpha \in I} \text{Hom}(H, G_\alpha).$$

Note the order in the Hom matters.

B.2 Free Abelian Group

Definition B.2.1 (Free Abelian group). Given an Abelian group $(G, +)$, we say G is a *free Abelian group* if there exists a collection of elements $\{g_\alpha\}_{\alpha \in J}$ in G such that $\{g_\alpha\}_{\alpha \in J}$ forms a **basis** of G , i.e., for all $g \in G$, $\exists! n_\alpha \in \mathbb{Z}$ for all $\alpha \in J$ such that

$$g = \sum_{\alpha \in J} n_\alpha g_\alpha$$

with finitely many non-zero n_α .

Remark. If G is a free Abelian group, and $\{g_\alpha\}_{\alpha \in J}$ is a basis, then for every $\alpha \in J$, $\langle g_\alpha \rangle$ is an infinite cyclic group since

$$n \cdot g_\alpha = 0 = 0 \cdot g_\alpha \Rightarrow n = 0.$$

And from Definition B.2.1, we have

$$G = \bigoplus_{\alpha \in J} \langle g_\alpha \rangle.$$

Conversely, assume there are a collection of infinite cyclic group $\langle g_\alpha \rangle$ for $\alpha \in I$ in G such that

$$G = \bigoplus_{\alpha \in I} \langle g_\alpha \rangle,$$

then $\{g_\alpha\}_{\alpha \in I}$ is a basis of G , hence G is a free Abelian group.

Proposition B.2.1. If G is an Abelian group, then the following are equivalent.

- (1) G is a free Abelian group.
- (2) G is an internal direct sum of some infinite cyclic groups.
- (3) G is isomorphic to the external direct sum of some additive groups of integers \mathbb{Z} .

Proof. We see that 1. \Leftrightarrow 2. is already proved. And for 2. \Leftrightarrow 3., this follows directly from the relation between internal and external direct sum. ■

Now, consider G as a [free Abelian group](#), then

$$u: G \xrightarrow{\cong} \bigoplus_{\alpha \in I} \mathbb{Z}$$

for some I . Denote $e_\alpha := i_\alpha(1) \in \bigoplus_{\alpha \in I} \mathbb{Z}$, where $i_\alpha: \mathbb{Z} \rightarrow \bigoplus_{\alpha \in I} \mathbb{Z}$ is the canonical embedding, i.e., $e_\alpha = (g_\alpha)_{\alpha \in I} \in \bigoplus_{\alpha \in I} \mathbb{Z}$, where

$$g_\beta = \begin{cases} 1, & \text{if } \beta = \alpha; \\ 0, & \text{if } \beta \neq \alpha. \end{cases}$$

Moreover, denote ϵ_α as the image of e_α under the isomorphism u , namely $\epsilon_\alpha = u^{-1}(e_\alpha)$, then $\{\epsilon_\alpha\}_{\alpha \in I}$ is a basis of G .

Now, for every [Abelian group](#) H , we have

$$\begin{array}{ccc} \text{Hom}(G, H) & \xleftarrow[\cong]{\circ u} & \text{Hom}\left(\bigoplus_{\alpha \in I} \mathbb{Z}, H\right) \\ & \searrow \cong & \downarrow \varphi \\ & & \prod_{\alpha \in I} \text{Hom}(\mathbb{Z}, H) \\ & & \downarrow \cong \\ & & \prod_{\alpha \in I} H \end{array} \quad \begin{array}{ccc} f & \xrightarrow{\quad} & f \circ u^{-1} \\ & \nwarrow & \downarrow \\ & & (f \circ u^{-1} \circ i_\alpha)_{\alpha \in I} \\ & \nwarrow & \downarrow \\ & & (f \circ u^{-1} \circ i_\alpha(1))_{\alpha \in I} \end{array}$$

where φ is the homeomorphism defined in [here](#), and the homeomorphism

$$\prod_{\alpha \in I} \text{Hom}(\mathbb{Z}, H) \xrightarrow{\cong} \prod_{\alpha \in I} H$$

is trivial since every $f \in \prod_{\alpha \in I} \text{Hom}(\mathbb{Z}, H)$ corresponds to $f(1) \in H$ uniquely. We see that

$$f \circ u^{-1} \circ i_\alpha(1) = f \circ u^{-1}(e_\alpha) = f(\epsilon_\alpha).$$

In other words, for all [Abelian group](#) H , a morphism from the set $\{\epsilon_\alpha\}_{\alpha \in I}$ to H can be uniquely extended to the group a homomorphism from G to H .

Remark. This means, to determine $\text{Hom}(G, H)$, we only need to determine where each base element in G will map to in H , and this is why it's *free*.

We now want to generate [free Abelian group](#) by a set. Roughly speaking, given a set S , we can generate a [free Abelian group](#) Z by defining

$$Z := \left\{ \sum_{x \in S} n_x x \mid n_x \in \mathbb{Z}, \# \text{ non-zero elements in } n_x < \infty \right\}$$

with the naturally defined $+$. Formally, we have the following.

Definition B.2.2 (Free Abelian group generated by a set). Given a set S , the [free Abelian group generated by \$S\$](#) $(Z, +)$ is defined as

$$Z := \{f: S \rightarrow \mathbb{Z} \mid \text{only finitely many } x \in S \text{ such that } f(x) \neq 0\},$$

with

$$\begin{aligned} +: Z \times Z &\rightarrow Z \\ (f, g) &\mapsto f + g. \end{aligned}$$

Remark. $\{\phi_x \mid x \in S\}$ forms a basis of Z , where $\phi_x: S \rightarrow \mathbb{Z}$ such that

$$y \mapsto \phi_x(y) = \begin{cases} 1, & \text{if } y = x; \\ 0, & \text{if } y \neq x \end{cases}$$

is the characteristic function at x . We see this by for all $f \in S$, $f = \sum_{x \in S} f(x)\phi_x$, which is uniquely defined. Hence, $(Z, +)$ is a **free Abelian group**.

Note. Note that

$$\begin{aligned} S &\xleftrightarrow{1:1} \{\phi_x \mid x \in S\} \\ x &\mapsto \phi_x. \end{aligned}$$

Hence, we often denote the element $\sum_{x \in S} \underbrace{n_x}_{f(x)} \phi_x$ in Z as

$$\sum_{x \in S} n_x \cdot x.$$

Theorem B.2.1 (The universal property of free Abelian group generated by a set). Denote a canonical embedding $i: S \rightarrow Z$, $x \mapsto \phi_x$. Then for all **Abelian group** H and $f: S \rightarrow H$, there exists a unique group homomorphism

$$\tilde{f}: Z \rightarrow H$$

such that $\tilde{f} \circ i = f$.

Proof. We define

$$\tilde{f}\left(\sum_{x \in S} n_x \cdot x\right) := \sum_{x \in S} n_x f(x),$$

and the uniqueness is obvious. ■

Note that we can use the above **universal property** to describe a **free Abelian group** since we have the following.

Proposition B.2.2. Given Z' as another **Abelian group** and $i': S \rightarrow Z'$ as another canonical embedding such that for all **Abelian group** H and $f: S \rightarrow H$, there exists a unique group homomorphism $\tilde{f}: Z' \rightarrow H$ such that $\tilde{f} \circ i' = f$, then

$$Z' \cong Z.$$

Namely, we can describe a **free Abelian group** by its **universal property** uniquely up to isomorphism.

Theorem B.2.2. Assume G is a **free Abelian group**. Assume there exists a finite basis $\{g_1, \dots, g_n\}$ of G , and also assume that there exists another basis $\{h_\alpha\}_{\alpha \in I}$. Then we have

$$\text{card}(I) < \infty,$$

specifically, we have

$$\text{card}(I) = n.$$

Proof. Firstly, we observe that if we can show

$$\text{card}(I) \leq n,$$

then by swapping $\{h_\alpha\}_{\alpha \in I}$ and $\{g_\alpha\}_{\alpha \in I}$, we will have $\text{card}(I) = n$.

Suppose I is an infinite set, then we can find $h_{\alpha_1}, \dots, h_{\alpha_m}$ such that $m > n$ and $h_{\alpha_i} \neq h_{\alpha_j}$ for

$i \neq j$. Then since $\{g_\alpha\}_{\alpha \in I}$ is a basis, we have

$$h_{\alpha_i} = \sum_{j=1}^n k_i^j g_j, \forall i = 1, \dots, m.$$

Specifically, we have

$$\begin{pmatrix} h_{\alpha_1} \\ \vdots \\ h_{\alpha_m} \end{pmatrix} = \underbrace{\begin{pmatrix} k_1^1 & k_1^2 & \dots & k_1^n \\ \vdots & \vdots & \ddots & \vdots \\ k_m^1 & k_m^2 & \dots & k_m^n \end{pmatrix}}_{K \in M_{m \times n}(\mathbb{Z}) \subset M_{m \times n}(\mathbb{Q})} \begin{pmatrix} g_1 \\ \vdots \\ g_n \end{pmatrix},$$

where $k_i^j \in \mathbb{Z}$. From linear algebra, we know that there exists $(r_1, \dots, r_m) \in \mathbb{Q}^m \setminus \{\vec{0}\}$ such that

$$(r_1, \dots, r_m)K = (0, \dots, 0).$$

Multiplying both sides with the common multiple of the denominator of r_i , we see that there exists $(\ell_1, \dots, \ell_m) \in \mathbb{Z}^m \setminus \{\vec{0}\}$ such that

$$\begin{aligned} & (\ell_1, \dots, \ell_m)K = (0, \dots, 0) \\ \Rightarrow & (\ell_1, \dots, \ell_m) \begin{pmatrix} h_{\alpha_1} \\ \vdots \\ h_{\alpha_m} \end{pmatrix} = (\ell_1, \dots, \ell_m)K \begin{pmatrix} g_1 \\ \vdots \\ g_n \end{pmatrix} = (0, \dots, 0) \\ \Rightarrow & \sum_{i=1}^m \ell_i h_{\alpha_i} = \vec{0} \text{ for } (\ell_1, \dots, \ell_m) \in \mathbb{Z}^m \setminus \{\vec{0}\} \\ \Rightarrow & \text{card}(I) < \infty. \end{aligned}$$

From the same argument, we see that $\text{card}(I) \leq n \Rightarrow \text{card}(I) = n$. ■

Remark. Furthermore, one can prove that if G is a [free Abelian group](#), then we can prove that any two bases of G are equinumerous, which handle the case that the basis is an infinite set.

This induces the following definition.

Definition B.2.3 (Rank). Let G be a [free Abelian group](#), the *rank* of G is the cardinality of any basis of G .

B.3 Finitely Generated Abelian Group

Since we're going to encounter some group as

$$\mathbb{Z} \oplus \mathbb{Z} / 2\mathbb{Z},$$

so it's useful to look into those finitely generated [Abelian group](#).

Let's start with a definition.

Definition B.3.1 (Torsion subgroup). Given an [Abelian group](#) G , we say that $g \in G$ has finite order if $\exists n \in \mathbb{Z}$ such that $n \cdot g = 0$. Specifically, we say that

$$T := \{g \in G \mid g \text{ has finite order}\}$$

is a *torsion subgroup*.

If $T = 0$ given G , we say that G is *torsion free*.

Note. Note that T is indeed a subgroup, since for any $g_1, g_2 \in T$, $g_1 + g_2 \in T$ from the fact that it still has finite order.

Remark. If G is a **free Abelian group**, then G is **torsion free**. Conversely, if G is **torsion free**, we can't deduce G is a **free Abelian group**. We see this from $(\mathbb{Q}, +)$. Firstly, we see that \mathbb{Q} is **torsion free**. Now, suppose \mathbb{Q} is a **free Abelian group**, then there exists a basis $\{r_\alpha\}_{\alpha \in I}$ of \mathbb{Q} such that $|I| > 1$. Now, consider $\alpha_1, \alpha_2 \in I$ such that $\alpha_1, \alpha_2 \in I$, for $r_{\alpha_1}, r_{\alpha_2}$, there exists $n, m \in \mathbb{Z}$ and $n, m \neq 0$ such that

$$nr_{\alpha_1} + mr_{\alpha_2} = 0 \Rightarrow n = m = 0 \nmid$$

B.3.1 Classification of Finitely generated Abelian Group

Given a finitely generated **Abelian group** G , we may assume its generators are g_1, \dots, g_n . Let F be

$$F := \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{n \text{ times}}$$

then there are a natural surjective homomorphism

$$\varphi: F \rightarrow G, \quad e_i \mapsto g_i$$

where $e_i = (0, \dots, 0, \underset{i^{th}}{1}, 0, \dots, 0)$. Now, let $K := \ker \varphi$, we have

$$G \cong F / K.$$

Then we have the following lemma.

Lemma B.3.1. K is a finitely generated **Abelian group**.

Proof.

\mathbb{Z} is Noetherian, F is a finitely generated \mathbb{Z} -module
 $\Rightarrow F$ is Noetherian module
 $\Rightarrow K$ as a submodule of F is a finitely generated \mathbb{Z} -module
 $\Rightarrow K$ is a finitely generated **Abelian group**.

Please refer all the concepts above from [AM94]. ■

Hence, we may assume the generators of K as b_1, \dots, b_m . From the definition of K , we can further express b_i as

$$b_i = (b_{i1}, b_{i2}, \dots, b_{in}) \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix}_{n \times n}$$

for all $i = 1, \dots, m$. Denote all such row vectors b_i in a matrix B , namely

$$B := \begin{pmatrix} b_{11} & \dots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \dots & b_{mn} \end{pmatrix} \in M_{m \times n}(\mathbb{Z}),$$

then we have

$$\begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} = B \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix}.$$

Multiply a matrix on the right-hand side. Now, consider a $p \in \text{GL}(n; \mathbb{Z})$, then

$$\begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} = B \cdot \underbrace{P P^{-1}}_{\text{new basis}} \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix} = (BP) \cdot \begin{pmatrix} e'_1 \\ \vdots \\ e'_n \end{pmatrix},$$

where

$$P^{-1} \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix} =: \begin{pmatrix} e'_1 \\ \vdots \\ e'_n \end{pmatrix}.$$

We see that $B \cdot P$ is the coefficient matrix of generators b_1, \dots, b_m under the new basis e'_1, \dots, e'_n .

Multiply a matrix on the left-hand side. For a $A \in \text{GL}(m; \mathbb{Z})$, then

$$\begin{pmatrix} b'_1 \\ \vdots \\ b'_m \end{pmatrix} = Q \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix} = QB \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix},$$

since Q is invertible, hence b'_1, \dots, b'_m are also generators of K . We see that QB is the coefficient matrix of new generators b'_1, \dots, b'_m under basis e_1, \dots, e_n .

Generally $Q \cdot B \cdot P$ is the matrix representation of a particular set of F 's generators under a particular basis.

Proposition B.3.1. There exists $P \in \text{GL}(n; \mathbb{Z})$ and $Q \in \text{GL}(m; \mathbb{Z})$ such that

$$Q \cdot B \cdot P = \begin{pmatrix} d_1 & & & & \\ & \ddots & & & \\ & & d_k & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix},$$

where $d_i \in \mathbb{Z}^+$ and $d_1 \mid d_2 \mid \dots \mid d_k$.

Proof. In fact, P, Q can be taken as the multiplication of the following three types of square matrices:

- P_{ij} :

$$P_{ij} = \begin{pmatrix} 1 & & & & \\ & \ddots & & & \\ & & 0 & & 1_{(ij)} \\ & & & \ddots & \\ & 1_{(ji)} & & 0 & \\ & & & & \ddots & \\ & & & & & 1 \end{pmatrix},$$

where the effect of multiplying P_{ij} from the right is *swapping column i, j* .

- $P_i(c)$, where c is the identity in \mathbb{Z} , i.e., $c = \pm 1$:

$$P_i(c) = \begin{pmatrix} 1 & & & \\ & \ddots & & \\ & & c_{(ii)} & \\ & & & \ddots & \\ & & & & 1 \end{pmatrix},$$

where the effect of multiplying $P_i(c)$ from the right is *multiplying c to column i* .

- $P_{ij}(a)$, $a \in \mathbb{Z}$:

$$P_{ij} = \begin{pmatrix} 1 & & & \\ & \ddots & & \\ & & a_{(ij)} & \\ & & & \ddots & \\ & & & & 1 \end{pmatrix},$$

where the effect of multiplying $P_{ij}(a)$ from the right is *adding a times column i to column j* .

We see that these are *elementary column transformations* in linear algebra. In particular, if we multiply these matrices from the left, then it's called *elementary row transformations*.

That is to say, we're going to show

$$B = \begin{pmatrix} b_{11} & \dots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \dots & b_{mn} \end{pmatrix}$$

can become

$$\begin{pmatrix} d_1 & & & \\ & \ddots & & \\ & & d_k & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix},$$

$d_i \in \mathbb{Z}^+$, $d_1 \mid d_2 \mid \dots \mid d_k$ from *elementary column/row transformations*.

We now show the steps to make this happens.

- **Step 1.** Using elementary transformations, we make $b_{11} > 0$.
- **Step 2.** Using elementary transformations, we make b_{11} become a divisor of all elements in the first column and row.

We see that if $b_{11} \nmid b_{1i}$ for $i \neq 1$, we have $b_{1i} = r \cdot b_{11} + s$ where $0 < s < b_{11}$. Then we add $(-r)$ times the 1^{th} column to the i^{th} column and swapping the 1^{th} and the i^{th} column, which makes B becomes

$$\begin{pmatrix} s & \dots \\ \vdots & \ddots \end{pmatrix},$$

for $0 < s < b_{11}$. Since $\text{card}(\{n \in \mathbb{Z} \mid 0 < n < b_{11}\}) < \infty$, hence in finitely many steps we can make B becomes

$$\begin{pmatrix} d_1 & \dots \\ \vdots & \ddots \end{pmatrix},$$

where d_1 is a divisor of all other elements in the first column and row.

- **Step 3.** Using elementary transformations, we can multiply the first row by a proper integer and add it to the other rows, do the same but for columns also, then we can make B becomes

$$\begin{pmatrix} d_1 & 0 & \dots & 0 \\ 0 & & & \\ \vdots & & B_1 & \\ 0 & & & \end{pmatrix}.$$

- **Step 4.** We iteratively apply Step 1. to step 3., we make B into

$$\begin{pmatrix} d_1 & & & & \\ & \ddots & & & \\ & & d_k & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix},$$

where $d_i \in \mathbb{Z}^+$.

- **Step 5.** Using elementary transformations, by swapping columns and rows, we may assume $d_1 \leq d_2 \leq \dots \leq d_k$.
- **Step 6.** Using elementary transformations, we can make B into

$$\begin{pmatrix} d'_1 & & & & \\ & \ddots & & & \\ & & d'_\ell & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix}$$

such that $0 < d'_1 \leq \dots \leq d'_\ell$, $d'_1 \mid d'_2 \mid \dots \mid d'_\ell$ since if $d_1 \nmid d_i$ for some $i \in \{2, \dots, k\}$, then

$$\begin{pmatrix} d_1 & & & & \\ & \ddots & & & \\ & & d_k & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix} \rightarrow \begin{pmatrix} d_1 & d_i & & & \\ & \ddots & & & \\ & & d_k & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix},$$

then from Step 2., we have

$$\begin{pmatrix} s & \dots \\ \vdots & \ddots \end{pmatrix}$$

where $0 < s < d_1$ and s is a divisor of all other elements in the first row and column. Now, we repeat Step 3. to Step 5., we obtain

$$\begin{pmatrix} \tilde{d}_1 & & & & \\ & \ddots & & & \\ & & \tilde{d}_j & & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix}$$

where $\tilde{d}_1 \leq \dots \leq \tilde{d}_j$ such that $\tilde{d}_1 < d_1$. Since there are only finitely many integers which is

smaller than d_1 , we see that by repeating these steps, we can always make

$$\begin{pmatrix} d_1 & & & \\ & \ddots & & \\ & & d_k & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix}$$

into

$$\begin{pmatrix} \tilde{d}_1 & & & \\ & \ddots & & \\ & & \tilde{d}_p & \\ & & & 0 & \\ & & & & \ddots \end{pmatrix}$$

such that $d'_1 \mid d'_i$ for all $i \neq 1$ and $d'_1 \leq d'_2 \leq \dots \leq d'_p$. By the same idea of Step 3., we have the desired matrix.

Since all operations are elementary and there are only finitely many of them, hence the result follows. \blacksquare

From the definition of $Q \cdot B \cdot P$ and [Proposition B.3.1](#), there exists a basis e'_1, \dots, e'_n of F such that K has finitely many generators $d_1 e'_1, \dots, d_k e'_k$, hence

$$G \cong \mathbb{Z}/d_1\mathbb{Z} \oplus \mathbb{Z}/d_2\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/d_k\mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{n-k \text{ times}}.$$

This leads to the following important theorem.

Theorem B.3.1 (Fundamental theorem of finitely generated Abelian group). Given a finitely generated Abelian group, either G is a free Abelian group, or there exists a unique set of $\{m_i \in \mathbb{Z} \mid m_i > 1, i = 1, \dots, t\}$ such that $m_1 \mid m_2 \mid \dots \mid m_t$ and a unique non-negative integer s such that

$$G \cong \mathbb{Z}/m_1\mathbb{Z} \oplus \mathbb{Z}/m_2\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{s \text{ times}}.$$

Proof. We need to show both uniqueness and existence.

Existence. From [Proposition B.3.1](#), we obtain a basis e'_1, \dots, e'_n of F and a basis $d_1 e'_1, \dots, d_k e'_k$ in K such that $d_1 \mid \dots \mid d_k$. Let

$$(d_1, \dots, d_k) = (1, \dots, 1, m_1, \dots, m_t),$$

which implies

$$\begin{aligned} G &\cong F/K \\ &\cong \mathbb{Z}/d_1\mathbb{Z} \oplus \mathbb{Z}/d_2\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/d_k\mathbb{Z} \oplus \mathbb{Z} \oplus \dots \oplus \mathbb{Z} \\ &= \mathbb{Z}/1\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/1\mathbb{Z} \oplus \mathbb{Z}/m_1\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z} \oplus \mathbb{Z} \oplus \dots \oplus \mathbb{Z} \\ &= \mathbb{Z}/m_1\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{\exists! s \text{ times}}. \end{aligned}$$

Uniqueness. Under the isomorphism $\mathbb{Z}/m_1\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{s \text{ times}}$, we see that

$$\mathbb{Z}/m_1\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z}$$

corresponds to G 's **torsion subgroup** T , which implies

$$G/T \cong \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{s \text{ times}},$$

which further implies G/T is a **free Abelian group** with

$$\text{rk}(G/T) = s,$$

which proves the uniqueness of s .

The proof of the uniqueness of m_i are long and tedious, we refer to [Arm13]. ■

Definition B.3.2 (Invariant factor). We call m_1, \dots, m_t obtained from [Theorem B.3.1](#) the *invariant factor*.

Lemma B.3.2. Given a positive integer m such that

$$m = p_1^{n_1} \cdot \dots \cdot p_s^{n_s}$$

where $p \in \mathcal{P}$ are all prime and $p_i \neq p_j$ for $i \neq j$, with $n_i \in \mathbb{Z}^+$ for all i . Then

$$\mathbb{Z}/m\mathbb{Z} \cong \mathbb{Z}/p_1^{n_1}\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/p_s^{n_s}\mathbb{Z}.$$

Proof. We define ϕ as

$$\begin{aligned} \phi: \mathbb{Z}/m\mathbb{Z} &\rightarrow \mathbb{Z}/p_1^{n_1}\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/p_s^{n_s}\mathbb{Z} \\ \bar{n} &\mapsto (n + \langle p_1^{n_1} \rangle, \dots, n + \langle p_s^{n_s} \rangle). \end{aligned}$$

Then $\bar{n} \in \ker \phi \Leftrightarrow \forall_i p_i^{n_i} \mid n \Leftrightarrow m \mid n \Leftrightarrow \bar{n} = \bar{0}$. This means $\ker \phi = 0$, hence ϕ is an injection.

We now prove ϕ is a surjection. It's sufficient to prove that for all i ,

$$(0, \dots, 0, 1 + \langle p_i^{n_i} \rangle, 0, \dots, 0) \in \mathbb{Z}/p_1^{n_1}\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/p_s^{n_s}\mathbb{Z},$$

there exists an \bar{n} such that

$$\phi(\bar{n}) = (0, \dots, 0, 1 + \langle p_i^{n_i} \rangle, 0, \dots, 0).$$

Notice that for all $i \neq j$, $\langle p_i^{n_i} \rangle + \langle p_j^{n_j} \rangle \in \mathbb{Z}$, hence there exists $u_j \in \langle p_i^{n_i} \rangle$ and $v_j \in \langle p_j^{n_j} \rangle$ such that $u_j + v_j = 1$. Let n as

$$n = \prod_{i \neq j} (1 - u_j),$$

then

$$n + \langle p_i^{n_i} \rangle = 1 + \langle p_i^{n_i} \rangle, \quad n + \langle p_j^{n_j} \rangle = 0 + \langle p_j^{n_j} \rangle.$$

Above implies

$$\phi(\bar{n}) = (0, \dots, 0, 1 + \langle p_i^{n_i} \rangle, 0, \dots, 0),$$

hence ϕ surjects, so

$$\mathbb{Z}/m\mathbb{Z} \cong \mathbb{Z}/p_1^{n_1}\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/p_s^{n_s}\mathbb{Z}.$$

■

Combine [Theorem B.3.1](#) and [Lemma B.3.2](#), we see that we now only have

$$G \cong \mathbb{Z}/m_1\mathbb{Z} \oplus \mathbb{Z}/m_2\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/m_t\mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{s \text{ times}},$$

we can further decompose G into

$$G \cong \mathbb{Z} / p_1^{s_1} \mathbb{Z} \oplus \dots \oplus \mathbb{Z} / p_k^{s_k} \mathbb{Z} \oplus \underbrace{\mathbb{Z} \oplus \dots \oplus \mathbb{Z}}_{s \text{ times}},$$

where p_1, \dots, p_k are primes (which may includes repeated terms), $s_i \in \mathbb{Z}^+$ for all i .

Definition B.3.3 (Elementary divisors). The set

$$\{p_1^{s_1}, \dots, p_k^{s_k}\}$$

are called *elementary divisors* of G .

Theorem B.3.2 (Uniqueness of elementary divisors). **Elementary divisors** of a group G is unique.

Proof. Please refer to [Arm13]. ■

B.4 Homological Algebra

B.4.1 Exact Sequence

As previously seen. Given two **Abelian groups** A, B and the group homomorphism $\varphi: A \rightarrow B$, then we have

- $\ker \varphi = \{x \in A \mid \varphi(x) = 0\}$
- $\text{Im } \varphi = \{\varphi(x) \mid x \in A\}$
- $\text{coker } \varphi := B / \text{Im } \varphi$
- $\text{coIm } \varphi := A / \ker \varphi$

Consider a sequence of **Abelian** group homomorphism

$$\dots \longrightarrow A_{i-1} \xrightarrow{\phi_{i-1}} A_i \xrightarrow{\phi_i} A_{i+1} \longrightarrow \dots$$

We denote this sequence as S .

Definition B.4.1 (Exact). We say S is *exact* at A_i if

$$\text{Im } \phi_{i-1} = \ker \phi_i.$$

Remark. Definition B.4.1 is same as Definition 5.2.15.

Definition B.4.2 (Exact sequence). We call S is an *exact sequence* if it's **exact** at A_i for all i .

Remark. Specifically, consider the following two situations.

- We say

$$A_0 \longrightarrow A_1 \longrightarrow A_2 \longrightarrow \dots$$

is an **exact sequence** if it's **exact** at A_i for all $i \geq 1$.

- We say

$$\dots \longrightarrow A_{-2} \longrightarrow A_{-1} \longrightarrow A_0$$

is an **exact sequence** if it's **exact** at A_i for all $i \leq -1$.

Remark. Denote \circ as a trivial [Abelian group](#), then

$A \xrightarrow{\phi} B \longrightarrow \circ$ is an [exact sequence](#) $\Leftrightarrow \phi$ is a surjective homomorphism;

conversely,

$\circ \longrightarrow B \xrightarrow{\phi} A$ is an [exact sequence](#) $\Leftrightarrow \phi$ is an injective homomorphism.

Definition B.4.3 (Short exact sequence). A *short exact sequence* is an [exact sequence](#) such that it has the following form

$$\circ \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow \circ.$$

Remark. Let $B \xrightarrow{\psi} C$ as a surjective homomorphism and $K = \ker \psi$, and we denote $K \xrightarrow{i} B$ as an injection. Then

$$\circ \longrightarrow K \xrightarrow{i} B \xrightarrow{\psi} C \longrightarrow \circ$$

is a [short exact sequence](#). Conversely, if

$$\circ \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow \circ$$

is a [short exact sequence](#), then ϕ is an injective homomorphism since it is [exact](#) at A , and ψ is a surjective homomorphism since it is [exact](#) at C , and $\phi(A) = \ker \psi$ since it is [exact](#) at B . This implies $\phi: A \rightarrow \phi(A) = \ker \psi$ is a group homeomorphism.

Example. Given A, B as [Abelian groups](#), then

$$\begin{aligned} \circ &\longrightarrow A \xrightarrow{i} A \oplus B \xrightarrow{\text{Proj}_2} B \longrightarrow \circ \\ a &\longmapsto (a, 0) \\ (a, b) &\longmapsto b \end{aligned}$$

is a [short exact sequence](#).

Example. We see that

$$\begin{aligned} \circ &\longrightarrow \mathbb{Z} \xrightarrow{i} \mathbb{Z} \xrightarrow{\text{Proj}_2} \mathbb{Z}/n\mathbb{Z} \longrightarrow \circ \\ k &\longmapsto k \cdot n \end{aligned}$$

for $n \in \mathbb{Z}_{\geq 1}$ is a [short exact sequence](#).

Definition B.4.4 (Isomorphism between sequences). Given A_\bullet and B_\bullet defined as two sequences of [Abelian group](#) homomorphisms

$$A_\bullet: \dots \longrightarrow A_i \xrightarrow{\phi_i} A_{i+1} \longrightarrow \dots$$

and

$$B_\bullet: \dots \longrightarrow B_i \xrightarrow{\psi_i} B_{i+1} \longrightarrow \dots$$

And we say a morphism α from A_\bullet to B_\bullet is a series of group homomorphisms $\alpha_i: A_i \rightarrow B_i$ for

all $i \in \mathbb{Z}$ such that the following diagram commutes.

$$\begin{array}{ccccccc} \dots & \longrightarrow & A_i & \xrightarrow{\phi_i} & A_{i+1} & \longrightarrow & \dots \\ & & \downarrow \alpha_i & & \downarrow \alpha_{i+1} & & \\ \dots & \longrightarrow & B_i & \xrightarrow{\psi_i} & B_{i+1} & \longrightarrow & \dots \end{array}$$

Additionally, if for all i , α_i is a group homeomorphism, then we say $\alpha: A_\bullet \rightarrow B_\bullet$ is a homeomorphism.

Definition B.4.5 (Split short exact sequence). Given a [short exact sequence](#)

$$0 \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow 0$$

we say it is *split* if there exists a group homeomorphism $\theta: B \rightarrow A \oplus C$ such that

$$\begin{array}{ccccccc} 0 & \longrightarrow & A & \xrightarrow{\phi} & B & \xrightarrow{\psi} & C \longrightarrow 0 \\ & & \downarrow \text{id} & & \downarrow \theta & & \downarrow \text{id} \\ 0 & \longrightarrow & A & \longrightarrow & A \oplus C & \longrightarrow & C \longrightarrow 0 \end{array}$$

is the [isomorphism](#) between these two [short exact sequences](#).

Remark. Given [split short exact sequence](#)

$$0 \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow 0$$

and θ defined in [Definition B.4.5](#), let $i: A \rightarrow A \oplus C$, $a \mapsto (a, 0)$ and $j: C \rightarrow A \oplus C$, $c \mapsto (0, c)$ are two canonical embeddings, then we have

$$A \oplus C = i(A) \oplus j(C).$$

Consider $\theta^{-1}: A \oplus C \xrightarrow{\cong} B$, then

$$B = \theta^{-1}(i(A)) \oplus \theta^{-1}(j(C)).$$

Since the diagram in [Definition B.4.5](#) commutes, hence

$$\theta^{-1}(i(A)) = \theta^{-1} \circ i(A) = \phi(A),$$

hence

$$B = \phi(A) \oplus \underbrace{\theta^{-1}(j(C))}_D,$$

which implies $\psi|_D: D \rightarrow C$ is a group homeomorphism. We see that

$$0 \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow 0$$

[split](#) implies $B = \phi(A) \oplus D$ and $\psi|_D: D \xrightarrow{\cong} C$.

Conversely, if $B = \phi(A) \oplus D$ and $\psi|_D: D \xrightarrow{\cong} C$, then there exists a θ

$$\begin{aligned} \theta: B &\rightarrow A \oplus C \\ \phi(a) + d &\mapsto (a, \psi(d)) \end{aligned}$$

for $a \in A, d \in D$ such that

$$\begin{array}{ccccccc} \circ & \longrightarrow & A & \xrightarrow{\phi} & B & \xrightarrow{\psi} & C \longrightarrow \circ \\ & & \downarrow \text{id} & & \downarrow \theta & & \downarrow \text{id} \\ \circ & \longrightarrow & A & \longrightarrow & A \oplus C & \longrightarrow & C \longrightarrow \circ \end{array}$$

$$\begin{array}{ccc} \phi(a) + d & \longmapsto & \psi(d) \\ \downarrow & & \downarrow \\ (a, \psi(d)) & \longmapsto & \psi(d) \end{array}$$

commutes.

Hence, for a [short exact sequence](#) $\circ \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow \circ$ is [split](#) if and only if $B = \phi(A) \oplus D$ and $\psi|_D : D \xrightarrow{\cong} C$.

Remarkably, let $\circ \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow \circ$ is a [split short exact sequence](#), then D constructed above is not unique. To see this, consider

$$\begin{array}{ccccccc} \circ & \longrightarrow & \mathbb{Z} & \xrightarrow{i} & \mathbb{Z} \oplus \mathbb{Z} & \xrightarrow{\text{Proj}_2} & \mathbb{Z} \longrightarrow \circ \\ & & & & n \longmapsto (n, 0) & & \\ & & & & (n, m) \longmapsto m & & \end{array}$$

We have $\mathbb{Z} \oplus \mathbb{Z} = i(\mathbb{Z}) \oplus j(\mathbb{Z})$ where $j: \mathbb{Z} \rightarrow \mathbb{Z} \oplus \mathbb{Z}, n \mapsto (0, n)$. We see that we can let $D := j(\mathbb{Z})$. Meanwhile, we can also let

$$D := \{(n, n) \mid n \in \mathbb{Z}\} < \mathbb{Z} \oplus \mathbb{Z}$$

such that $\mathbb{Z} \oplus \mathbb{Z} = i(\mathbb{Z}) \oplus D$.

Example (Non-split short exact sequence). We see that

$$\begin{array}{ccccccc} \circ & \longrightarrow & \mathbb{Z} & \xrightarrow{i} & \mathbb{Z} & \xrightarrow{\text{Proj}_2} & \mathbb{Z}/n\mathbb{Z} \longrightarrow \circ \\ & & & & k \longmapsto k \cdot n & & \end{array}$$

is not a [split short exact sequence](#), since if it is, then

$$\begin{array}{ccc} \mathbb{Z} \oplus \mathbb{Z} / n\mathbb{Z} & \cong & \mathbb{Z} \\ (0, 1) & \mapsto & k, \end{array}$$

which is a contradiction since \mathbb{Z} is [torsion-free](#) while $\mathbb{Z} \oplus \mathbb{Z} / n\mathbb{Z}$ is not.

Lemma B.4.1 (Splitting lemma). If $\circ \longrightarrow A \xrightarrow{\phi} B \xrightarrow{\psi} C \longrightarrow \circ$ is a [short exact sequence](#), then the following are equivalent.

- (1) This [short exact sequence](#) [split](#).
- (2) $\exists p: B \rightarrow A$ such that $p \circ \phi = \text{id}_A$.
- (3) $\exists q: C \rightarrow B$ such that $\psi \circ q = \text{id}_C$.

Proof. • 1. \Rightarrow 2. Let $\theta: B \xrightarrow{\cong} A \oplus C$ such that it's the [isomorphism](#) which makes the following

diagram commutes.

$$\begin{array}{ccccccc}
 \circ & \longrightarrow & A & \xrightarrow{\phi} & B & \xrightarrow{\psi} & C \longrightarrow \circ \\
 & & \downarrow \text{id} & & \downarrow \theta & & \downarrow \text{id} \\
 \circ & \longrightarrow & A & \xrightarrow{i} & A \oplus C & \longrightarrow & C \longrightarrow \circ \\
 & & & \nwarrow \text{Proj}_1 & & &
 \end{array}$$

Then we let $p := \text{Proj}_1 \circ \theta$, then

$$p \circ \phi = \text{Proj}_1 \circ \theta \circ \phi = \text{Proj}_1 \circ i = \text{id}_A.$$

- 1. \Rightarrow 3. Let $\theta: B \xrightarrow{\cong} A \oplus C$ such that it's the **isomorphism** which makes the following diagram commutes.

$$\begin{array}{ccccccc}
 \circ & \longrightarrow & A & \xrightarrow{\phi} & B & \xrightarrow{\psi} & C \longrightarrow \circ \\
 & & \downarrow \text{id} & & \downarrow \theta & & \downarrow \text{id} \\
 \circ & \longrightarrow & A & \longrightarrow & A \oplus C & \xrightarrow{\text{Proj}_2} & C \longrightarrow \circ \\
 & & & & \nwarrow j & &
 \end{array}$$

Then we let $q := \theta^{-1} \circ j$, then for all $c \in C$, we have

$$\psi \circ q(c) = \psi(\theta^{-1}(j(c))) = \text{Proj}_2 \circ \theta(\theta^{-1}(j(c))) = \text{Proj}_2(j(c)) = c,$$

hence $\psi \circ q = \text{id}_C$.

- 2. \Rightarrow 1. We have

$$\circ \longrightarrow A \xrightleftharpoons[p]{\phi} B \xrightarrow{\psi} C \longrightarrow \circ$$

where $p \circ \phi = \text{id}_A$. We claim that $B = \phi(A) \oplus \ker(p)$ since for every $b \in B$, $\phi(p(b)) \in \phi(A)$, and

$$b = \underbrace{\phi(p(b))}_{\in \phi(A)} + \underbrace{(b - \phi(p(b)))}_{\in \ker(p)}$$

from the fact that

$$p(b - \phi(p(b))) = p(b) - p \circ \phi(p(b)) = p(b) - p(b) = 0.$$

We need to show the uniqueness also. Suppose $b = \phi(a_1) + d_1 = \phi(a_2) + d_2$, $a_1, a_2 \in A$, $d_1, d_2 \in \ker(p)$. We see that

$$\phi(a_1 - a_2) = d_2 - d_1 \Rightarrow p(\phi(a_1 - a_2)) = 0 \Rightarrow a_1 = a_2 \Rightarrow d_1 = d_2.$$

Finally, we claim that

$$\psi|_{\ker(p)} : \ker(p) \rightarrow C$$

is a group homeomorphism. But it's obvious that $\psi|_{\ker(p)}$ are both surjective and injective.

- 3. \Rightarrow 1. We have

$$\circ \longrightarrow A \xrightarrow{\phi} B \xrightleftharpoons[q]{\psi} C \longrightarrow \circ$$

where $\psi \circ q = \text{id}_C$. We claim that $B = \phi(A) \oplus q(C)$ since for every $b \in B$,

$$b = \underbrace{(b - q(\psi(b)))}_{\in \ker(\psi) = \text{Im}(\phi)} + \underbrace{q(\psi(b))}_{\in q(C)},$$

which implies $B = \phi(A) + q(C)$. We can also prove that

$$B = \phi(A) \oplus q(C)$$

similarly. ■

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