

MATH592

Introduction to Algebraic Topology

Pingbang Hu

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Abstract

This course will use [HPM02] as the main text, but the order may differ here and there. Enjoy this fun course!

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Lecture 1: Homotopies of Maps

05 Jan. 10:00

1 Foundation of Algebraic Topology

1.1 Homotopy

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

Definition 1.1 (Homotopy, homotopic, nullhomotopic). Let X, Y be topological spaces. Let $f, g: X \rightarrow Y$ continuous maps. Then 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 $F(x, t)$.

If a homotopy exists between f and g , we say they are *homotopic* and write

$$f \simeq g.$$

If f is homotopic to a constant map, we call it *nullhomotopic*.

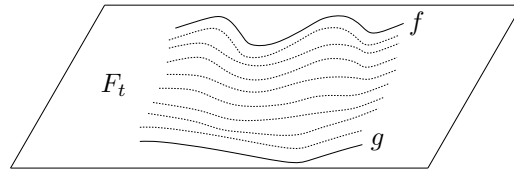


Figure 1: The continuous deforming from f to g described by F_t

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

Example. We first see some examples.

1. 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*.

2. 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** by considering

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

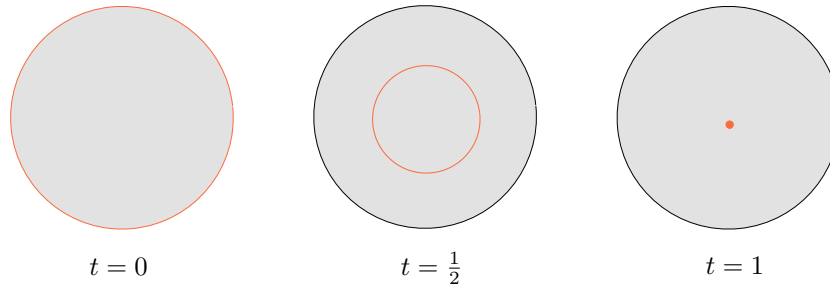


Figure 2: The illustration of $F_t(x)$

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**.

3. 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. We first see some exercises.

1. A subset $S \subseteq \mathbb{R}^n$ is star-shaped if

$$\exists x_0 \in S \text{ s.t. } \forall x \in S,$$

the line from x_0 to x lies in S .

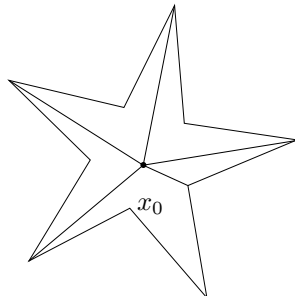


Figure 3: Star-shaped illustration

Show that $\text{id}: S \rightarrow S$ is [nullhomotopic](#).

Answer. Consider

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

which essentially just concentrates all points x to x_0 . ■

2. Suppose

$$X \xrightarrow[f_0]{f_1} Y \xrightarrow[g_0]{g_1} Z$$

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.

3. How could you show 2 maps are **not** [homotopic](#)?

Answer. We'll see! ■

Lecture 2: Homotopy Equivalence

07 Jan. 10:00

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

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

with the properties

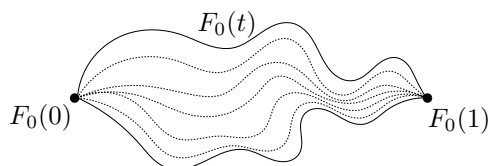
1. Continuous
2. $F_0(x) = f(x)$
3. $F_1(x) = g(x)$

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 1.2 (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 1.3 (Homotopy equivalence, homotopy inverse). A map $f: X \rightarrow Y$ is a *homotopy equivalence* if $\exists g: Y \rightarrow X$ such that

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

We say that X, Y are *homotopy equivalent*, and g is called *homotopy inverse* of f .

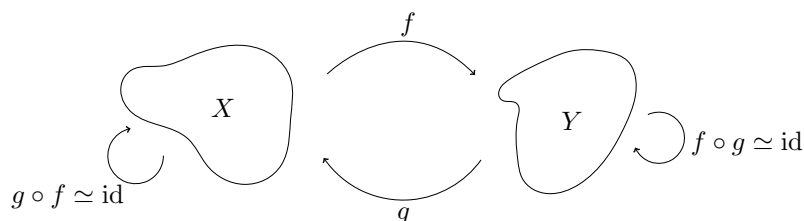
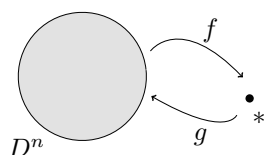


Figure 4: [Homotopy Equivalence](#)

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.



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** $F_t(x) = tx$.

Note. We say that a space is *contractible* if H is **homotopy equivalent** to a point.

Before doing exercises, we introduce two new concepts.

Definition 1.4 (Retraction, retract). Given $B \subseteq X$, a *retraction* from X to B is a map $f: X \rightarrow B$ (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

$$\begin{array}{ccc} B & \xrightarrow{i} & X \xrightarrow{r} B \\ & \searrow \text{roi} & \nearrow \end{array}$$

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

If r exists, B is a *retract* of X .

Definition 1.5 (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. We now see some problems.

1. 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.

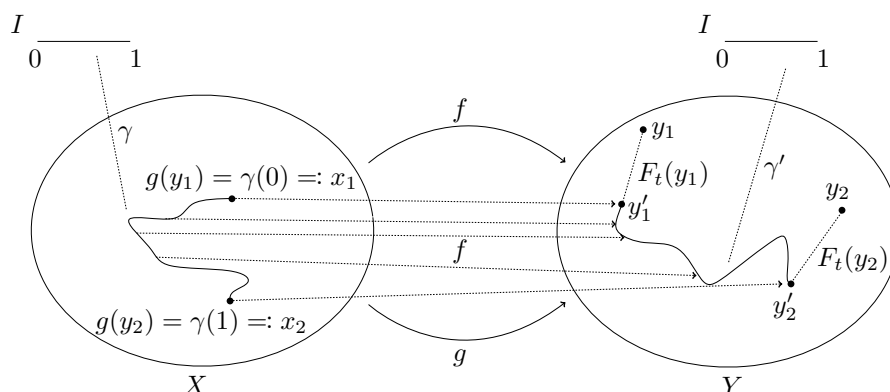


Figure 5: Demonstration of the proof.

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

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

Lecture 3: Deformation Retraction

10 Jan. 10:00

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](#).

Example. We can also show

1. S^1 is a **deformation retraction** of $D^2 \setminus \{0\}$. Indeed, since

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

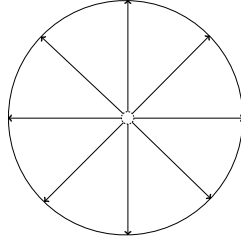


Figure 6: The **deformation retraction** of $D^2 \setminus \{0\}$ is just to *enlarge* that hole and push all the interior of D^2 to the boundary, which is S^1 .

2. \mathbb{R}^n **deformation retracts** to 0. Indeed, since

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

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

- dimension
- compactness
- etc.

are not **homotopy** invariants.

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

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 respect the equivalence relation.

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

Upshot: Möbius band $\simeq S^1 \simeq$ cylinder, hence the orientability is not **homotopy** invariant.

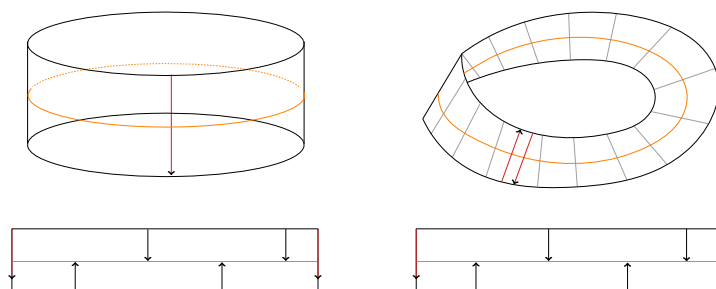


Figure 7: The deformation retraction for Cylinder and Möbius band

Lecture 4: Cell Complex (CW Complex)

12 Jan. 10:00

As previously seen. We saw that

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

1.3 CW Complexes

Example. Let's start with a few examples.

1. Constructing spheres:

- S^1 (up to homeomorphism¹)



- S^2
 - glue boundary of 2-disk to a point

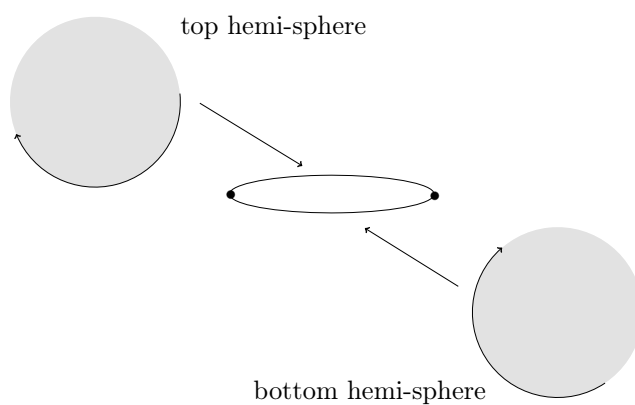
¹This is just the term for isomorphism in topology.

– glue 2 disks onto a circle

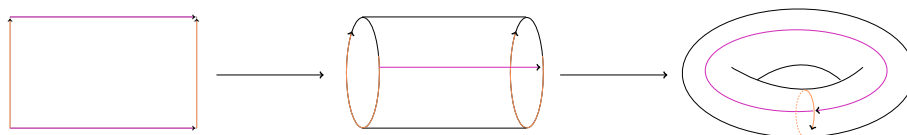


Figure 8: **Left:** Glue a 2-disk to a point along its boundary. **Right:** Glue 2 disks to S^1 .

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



• $T = S^1 \times S^1$



view as gluing instructions

vertex + 2 edges + 2-disks.

Specifically, we have

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

Example. Let's look at some examples.

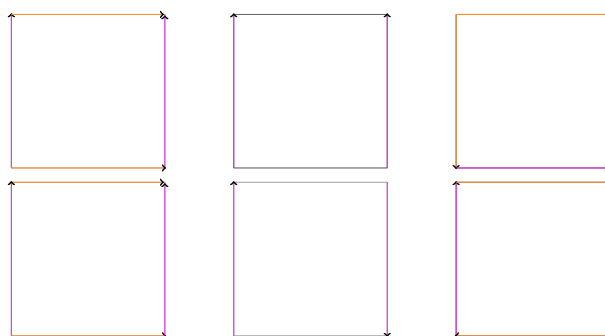
1. 0-dim **CW complex** is a discrete space.
2. 1-dim **CW complex** is a graph.
3. A **CW complex** X is finite if it has finitely many cells.

Definition 1.7 (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, $\mathbb{R}P$.

Answer. We see that

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

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

Lecture 5: Operation on Spaces

14 Jan. 10:00

1.4 Operations on CW Complexes

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 cell structure

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

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.

0-skeleton

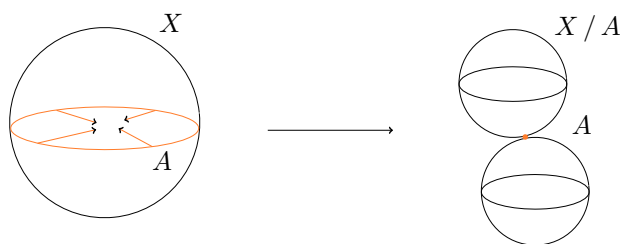
$$(X^0 - A^0) \amalg *$$

where $*$ is a point for A . 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. Here is some interesting examples.

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



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

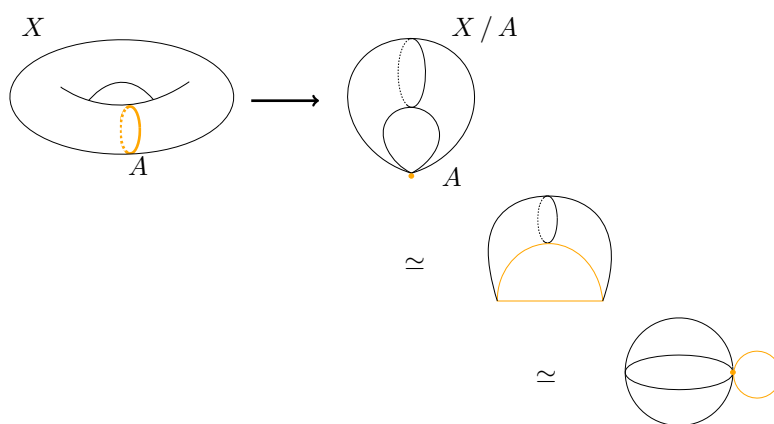


Figure 9: We see that X / A is **homotopy equivalent** to a 2-sphere **wedged** with a 1-sphere via extending the red point into a line, and then sliding the left point to the line along the 2-sphere towards the other points, forming a circle.

Lecture 6: A Foray into Category Theory

19 Jan. 10:00

1.5 Category Theory

We start with a definition.

Definition 1.8 (Category, object, morphism). A *category* \mathcal{C} is 3 pieces of data

- A class of *objects* $\text{Ob}(\mathcal{C})$
- $\forall X, Y \in \text{Ob}(\mathcal{C})$ a class of *morphisms* or arrows, $\text{Hom}_{\mathcal{C}}(X, Y)$.
- $\forall X, Y, Z \in \text{Ob}(\mathcal{C})$, 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.

Let's see some examples.

Example. We introduce some common *category*.

\mathcal{C}	$\text{Ob}(\mathcal{C})$	$\text{Mor}(\mathcal{C})$
<u>set</u>	Sets X	All maps of sets
<u>fset</u>	Finite sets	All maps
<u>Gp</u>	Groups	Group Homomorphisms
<u>Ab</u>	Abelian groups	Group Homomorphisms
<u>k-vect</u>	Vector spaces over k	k -linear maps
<u>Rng</u>	Rings	Ring Homomorphisms
<u>Top</u>	Topological spaces	Continuous maps
<u>Haus</u>	Hausdorff Spaces	Continuous maps
<u>hTop</u>	Topological spaces	Homotopy classes of continuous maps
<u>Top*</u>	Based topological spaces ²	Based maps ³

Remark. Any **diagram** plus composition law.

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

²Topological spaces with a distinguished base point $x_0 \in X$

³Continuous maps that presence base point $f: (x, x_0) \rightarrow (y, y_0)$ such that

$$f: X \rightarrow Y, \quad f(x_0) = y_0$$

is continuous.

Definition 1.9 (Monic, epic). A **morphism** $f: M \rightarrow N$ is *monic* if

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

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

Dually, f is *epic* if

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

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

Lemma 1.1. In set, Ab, Top, Gp, a map is **monic** if and only if f is injective, and **epic** if and only if f is surjective.

Proof. In 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 ,

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

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

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

■

1.5.1 Functor

After introducing the **category**, we then see the most important concept we'll use, a *functor*. Again, we start with the definition.

Definition 1.10 (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

21 Jan. 10:00

As previously seen. Assume that we initially have a commutative diagram in \mathcal{C} as

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

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 1.11 (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

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

Then, we see that in this case, when we apply a *contravariant functor* F , the diagram becomes

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

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

Example. Let see some examples.

1. Identity *functor*.

$$I: \mathcal{C} \rightarrow \mathcal{C}.$$

2. Forgetful *functor*.

•

$$F: \underline{\text{Gp}} \rightarrow \underline{\text{set}}, \quad G \mapsto G^4$$

such that

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

•

$$F: \underline{\text{Top}} \rightarrow \underline{\text{set}}, \quad X \mapsto X^5$$

such that

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

⁴ G is now just the underlying set of the group G .

⁵ X is now just the underlying set of the topological space X .

3. Free functor.

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

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

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

4.

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

If we are working on a basis, then we have

$$A \mapsto A^T.$$

Specifically, we care about two functors.

1.

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

where π_1 is so-called *fundamental group*.

2.

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

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

Let's see the formal definition.

1.6 Free Groups

Definition 1.12 (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 universal property.

If G is any group, $f: S \rightarrow G$ is any map of sets, f extends uniquely to group homomorphism $\bar{f}: F_S \rightarrow G$.

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

Note. This defines a *natural bijection*

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

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 1.13 (Adjoins functor). A **free** and **forgetful functor** is *ad-joins*.

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 1.2. 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

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

We'll show φ and ψ are inverses (and the unique isomorphism making above commute). Since we must have the following two commutative graphs.

$$\begin{array}{ccc} & F_S & \\ f \nearrow & \downarrow \mathrm{id}_{F_S} & \searrow f \\ S & & \\ f \searrow & \downarrow & \nearrow \\ & F_S & \end{array} \quad \begin{array}{ccc} & \tilde{F}_S & \\ f \nearrow & \downarrow \mathrm{id}_{\tilde{F}_S} & \searrow f \\ S & & \\ f \searrow & \downarrow & \nearrow \\ & \tilde{F}_S & \end{array}$$

Hence, we see that

$$\begin{array}{ccc} & F_S & \\ f \nearrow & \downarrow \psi & \searrow f \\ S & \longrightarrow & \tilde{F}_S \\ f \searrow & \downarrow \varphi & \nearrow \\ & F_S & \end{array} \quad \varphi \circ \psi = \mathrm{id}_{F_S} \quad \begin{array}{ccc} & \tilde{F}_S & \\ f \nearrow & \downarrow \varphi & \searrow f \\ S & \longrightarrow & F_S \\ f \searrow & \downarrow \psi & \nearrow \\ & \tilde{F}_S & \end{array} \quad \psi \circ \varphi = \mathrm{id}_{\tilde{F}_S}$$

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

24 Jan. 10:00

Example. In [category](#) [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\$](#) .

1.6.1 Constructing the Free Groups F_S

Proposition 1.1. The [free group](#) defined by the universal property exists.

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

Definition 1.14 (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 we can 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

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

2 The Fundamental Group

2.1 Path

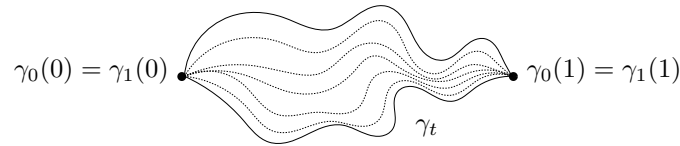
We start with the definition.

Definition 2.1 (Path). A *path* in a space X is a continuous map

$$\gamma: I \rightarrow X$$

where $I = [0, 1]$.

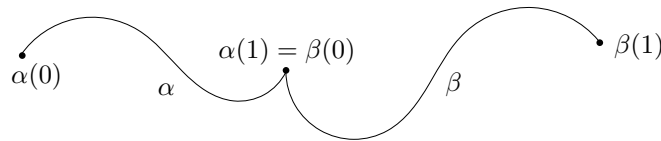
Definition 2.2 (Homotopy path). A *homotopy of paths* γ_0, γ_1 is a *homotopy* from γ_0 to γ_1 rel $\{0, 1\}$.



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 2.3 (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 2.4 (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.

Proof. 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

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

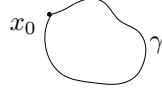
which shows that 0 and 1 are independent of t , hence γ and $\gamma \circ \phi$ are homotopic rel $\{0, 1\}$. ■

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

2.2 Fundamental Group

Definition 2.5 (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 $\text{rel}\{0, 1\}$ of **paths** $[\gamma]$ where γ is a **loop** with $\gamma(0) = \gamma(1) = x_0$ ^a

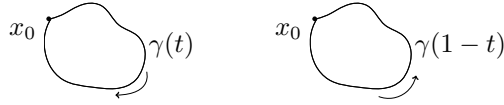


- Operation: **Composition of paths**.
- Identity: Constant loop γ based at x_0 such that

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

- 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 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 .

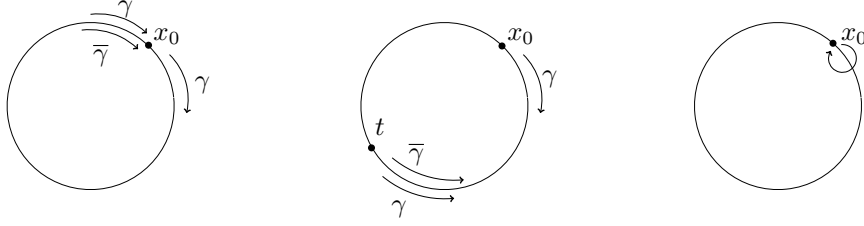


Figure 10: Illustration of F_t . Intuitively, the **path** $\gamma \cdot \bar{\gamma}$ is $x_0 \xrightarrow{\gamma} x_0 \xrightarrow{\bar{\gamma}} x_0$. But now, F_t is $x_0 \xrightarrow{\gamma} t \xrightarrow{\bar{\gamma}} x_0$. We can think of this **homotopy** is *pulling back* the turning point along the original **path**.

■

Theorem 2.1. If X is **path**-connected, then

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

Remark. We see that we can write $\pi_1(X)$ up to isomorphism given this result.

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

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

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

$$\gamma = \bar{h} \cdot \alpha \cdot h \in \pi_1(X, x_1)^6$$

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

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). ■

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.

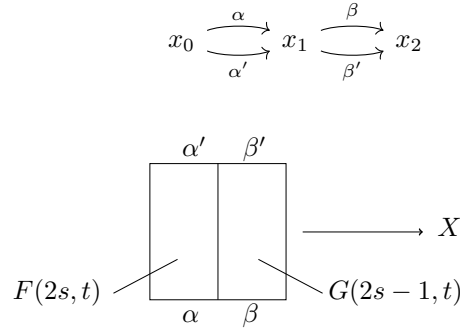
The followings are the properties about **homotopy path**. They are useful when we introduce **fundamental groupoid**.

Lemma 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 $\alpha \simeq_F \alpha' \text{ rel}\{0, 1\}$, $\beta \simeq_G \beta' \text{ rel}\{0, 1\}$, 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 $G(2s - 1, t)$.



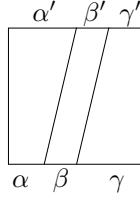
■

⁶Notice that this is indeed the case, one can verify this by the fact that $h: x_0 \rightarrow x_1$ and $\bar{h}: x_1 \rightarrow x_0$.

Lemma 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.

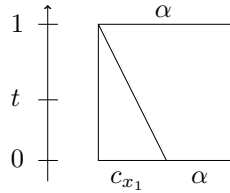


■

Lemma 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.

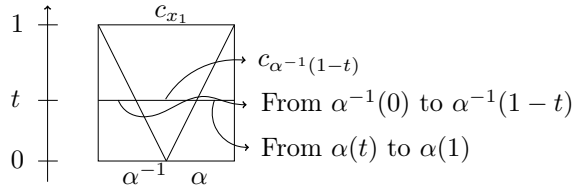


■

Lemma 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. ■

2.3 Fundamental Groupoid

This section is not covered in class, but it's a useful concept. The idea is that after giving [Definition 2.5](#), we see that we actually create a [fundamental group](#) at **every** point at X , furthermore, when we use [Theorem 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

$$\begin{aligned} c_x: [0, 1] &\rightarrow X \\ t &\mapsto x \end{aligned}$$

as a *constant loop*.

Definition 2.6 (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 2.5](#) defines a [groupoid](#), denoted by $\Pi(X)$.

Definition 2.7 (Fundamental groupoid). Let X denotes the space, then the category $\Pi(X)$ is a *fundamental groupoid of X* such that

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

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

- 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 $\langle \alpha \rangle \in \text{Hom}_{\Pi(X)}(p, q),$

$$\langle \alpha \rangle \circ 1_p = 1_q \circ \langle \alpha \rangle = \langle \alpha \rangle.$$

- 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 2.7](#), we need to show some of the definitions is 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 2.1](#).

- Identity: It follows that

$$\langle \alpha \rangle \circ 1_p = \langle c_p \cdot \alpha \rangle = \langle \alpha \rangle$$

from [Lemma 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 2.2](#).

Additionally, from [Lemma 2.4](#), we see that

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

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 $x \in X$.

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 2.1](#) is just a particular example as a [groupoid](#).

Lecture 9: Calculate Fundamental Group

26 Jan. 10:00

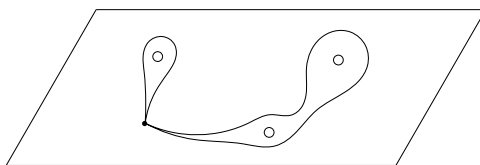


Figure 11: [Fundamental Group](#) is basically a *hole detector*!

2.4 Calculations with $\pi_1(S^n)$

Let's start with a simple theorem.

Theorem 2.2. The fundamental group of S^1 is

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

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

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

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.

Proof.

HW

Theorem 2.3. 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

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

Now, apply above to

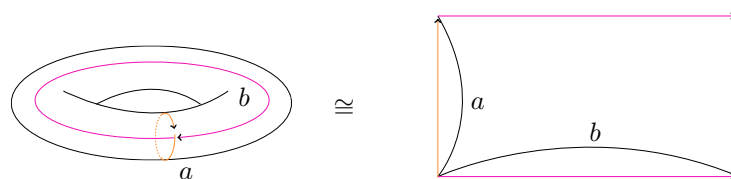
- [Paths](#) $I \rightarrow X \times Y$.
- [Homotopies of paths](#) $I \times I \rightarrow X \times Y$.

Corollary 2.1. 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. 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.

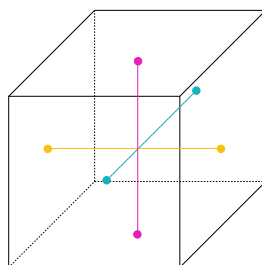


Figure 12: 3-torus with cube identified with parallel sides.

Example. We now see some examples.

1. $\pi_1(S^\infty \times S^1) \cong \mathbb{Z}$
2. $\pi_1(\mathbb{R}^2 \setminus \{0\}) \cong 0 \times \mathbb{Z} = \mathbb{Z}$ since

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

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

Theorem 2.4. π_1 is a **functor** such that

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

A map $f: X \rightarrow Y$ taking base point x_0 to y_0 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.,

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

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

Proof. We need to check

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

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

- $(\text{id}_{(X, x_0)})_* = \text{id}_{\pi_1(X, x_0)}$
- $(f_* \circ g_*) = (f \circ g)_*$

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

DIY



Lecture 10: Seifert-Van Kampen Theorem

26 Jan. 10:00

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

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

2.5 Seifert-Van Kampen Theorem

2.5.1 Free Product with Amalgamation

We first introduce a definition.

Definition 2.8 (Free product with amalgamation). Given some collections of groups $\{G_\alpha\}_\alpha$, the *free product*, denoted by $*_\alpha G_\alpha$ 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

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

- Operation: Concatenation of **words**.

Furthermore, 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

$$\begin{array}{ccc} S & \xrightarrow{i_{\alpha\beta}} & G_\alpha \\ i_{\beta\alpha} \downarrow & & \downarrow \\ G_\beta & \longrightarrow & G_\alpha *_S G_\beta \\ & \searrow & \downarrow \text{!} \\ & & X \end{array}$$

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

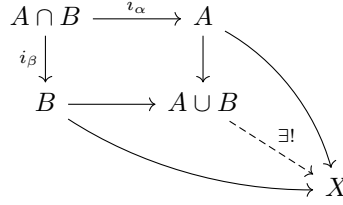
^bWe don't actually need $i_{\alpha\beta}, i_{\beta\alpha}$ to be inclusive as well.

^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.

Theorem 2.5 (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

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

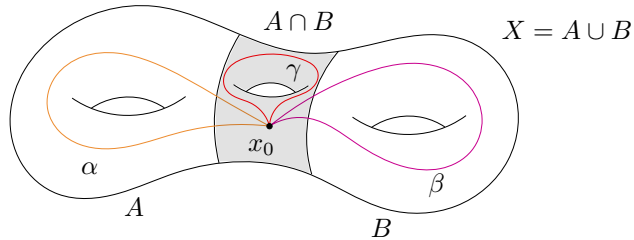
which is induced by the inclusion $i_{\alpha\beta}: A_{\alpha} \cap A_{\beta} \rightarrow A_{\alpha}$. We then take the quotient by the normal subgroup generated by

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

We'll defer the proof of [Theorem 2.5](#) until we get familiar with this theorem.⁷

Example. We first see a great visualization of the [Theorem 2.5](#).

⁷The proof can be found in [Section 2.7](#).



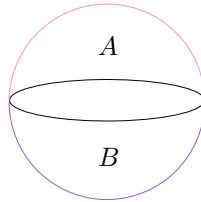
Intuitively we see the [fundamental group](#) of X , which is built by gluing A and B along their intersection. As the [fundamental group](#) of A and B glued along the [fundamental group](#) of their intersection. In essence, $\pi_1(X, x_0)$ is the quotient of $\pi_1(A) * \pi_1(B)$ by relations to impose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

Lecture 11: Group Presentations

31 Jan. 10:00

Example. We now see some applications of [Theorem 2.5](#).

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



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 $A \cap B \rightarrow A$ 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 $A \cap B \simeq S^1$.

2. In the case of torus, consider the following.

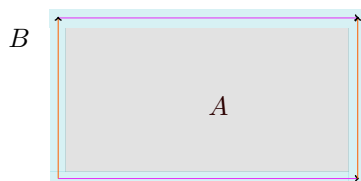


Figure 13: A is the interior, while B is the neighborhood of the boundary.

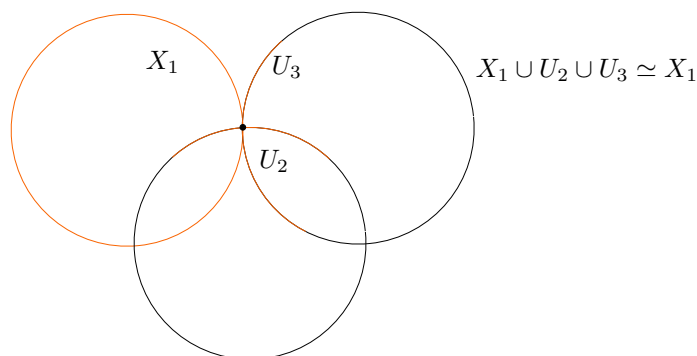
Now note that $A \simeq D^2$ and $B \simeq S^1 \vee S^1$, and since it's a thickening of the two loops around the torus in both ways, this suggests the question of how do we find $\pi_1(B)$? We grab a bit of knowledge from [Seifert Van Kampen Theorem](#) before we continue.

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

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

Proof. If we denote



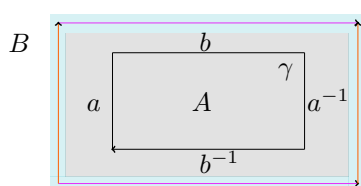
as C_n , then $\pi_1(C_n) \cong F_n$. Then we apply [Theorem 2.5](#) to $A_\alpha = X_\alpha \cup_\beta U_\beta$. Specifically, take $A_\alpha = X_\alpha \cup_\beta U_\beta \simeq X_\alpha$, where U_β is a neighborhood of x_β which [deformation retracts](#) to x_β . This makes A_α open as desired. ■

Corollary 2.2. 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 [example of torus](#), 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 13](#) to talk about this.



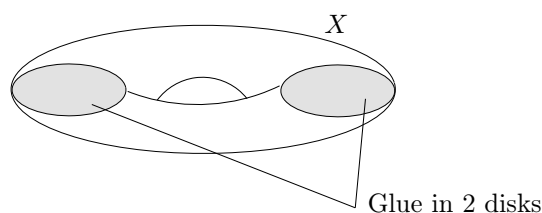
From this, we have

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

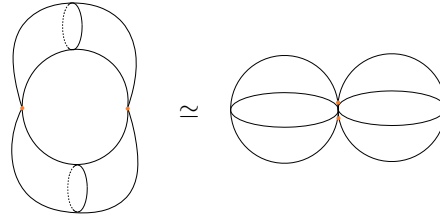
By [Seifert Van Kampen Theorem](#), we identify the image of γ in $\pi_1(B)[aba^{-1}b^{-1}]$ with its image in $\pi_1(A)$, which is just trivial. Therefore, we have

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

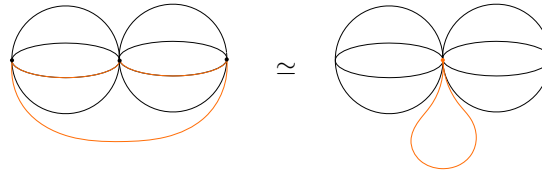
- Let's see the last example which illustrate the power of [Seifert Van Kampen Theorem](#). Start with a torus, and we glue in two disks into the hollow inside.



We'll call this space X , and our goal is to find $\pi_1(X)$. 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. Then $X \simeq \bigvee_n S^1$, so then

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

One way to do this is to convince yourself that you can do a [deformation retract](#) the plane onto the following [wedge](#).

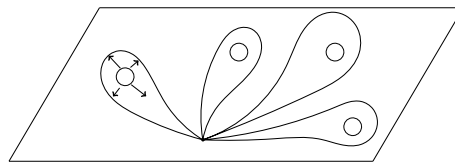


Figure 14: [Deformation retract](#) X onto [wedge](#).

2.6 Group Presentation

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

Definition 2.9 (Group presentation). A presentation $\langle S \mid R \rangle$ of a group G is

- S : set of *generators*
- R : set of *relators* (words in a generator and inverses)

such that

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

where $\langle R \rangle$ is a subgroup normally generated by the elements of R .

Definition 2.10 (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. $\mathbb{Z}^2 = \langle a, b \mid aba^{-1}b^{-1} \rangle$
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 2.6. 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 theorem⁸, $G \cong F_S / \ker \varphi$. In fact, we have $G = \langle S \mid R \rangle$. ■

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., $\psi(r) = 0$ 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.

⁸https://en.wikipedia.org/wiki/Isomorphism_theorems

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**.

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 π_1 of CW Complexes

2 Feb. 10:00

Let's first see an exercise.

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

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

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

2.6.1 Presentations for π_1 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. $\pi_1(X) = \pi_1(X^2)$.

Example. Given $G = \mathbb{Z}/n\mathbb{Z} = \langle a \mid a^n \rangle$, then we take a loop and then wind a 2-disk around the loop a for n times.

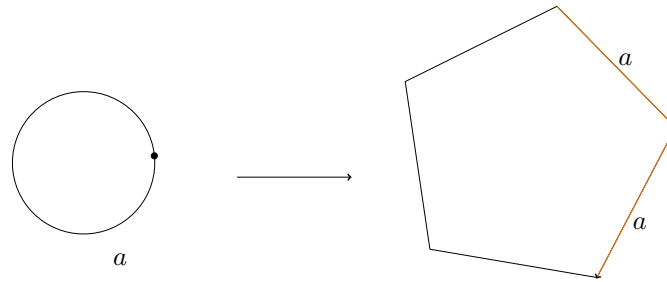


Figure 15: For $G = \mathbb{Z}/n\mathbb{Z} = \langle a \mid a^n \rangle$, we wind the boundary around a for n times.

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 .

Every group is then π_1 of some space.

Theorem 2.7. 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

Definition 2.11 (Graph, subgraph, tree, maximal tree). We import some topological definitions of graph theoretic concepts.

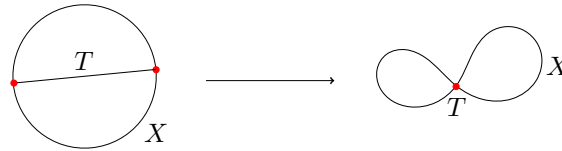
- A *graph* is a 1-dimensional CW complex.
- A *subgraph* is a subcomplex.
- A *tree* is a contractible graph.
- A *tree* in graph X (necessarily a subgraph) is *maximal* or *spanning* if it contains all the vertices.

Theorem 2.8. Every connected graph has a maximal tree. Every tree is contained in a maximal tree.

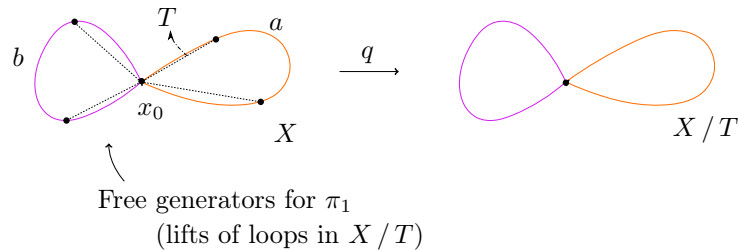
Corollary 2.3. Suppose X is a connected graph with basepoint x_0 . Then $\pi_1(X, x_0)$ is a free group.

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 .



The current plan is to calculate the fundamental group of CW complexes. 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

$$X^0 \coprod_{\alpha} I_{\alpha}.$$

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 we're done!

Our strategy now is to 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

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

We then see that $X = \bigcup_i X_i$.⁹ Now, let $Y_0 = X_0$. By induction, we'll assume that Y_i is a subgraph of X_i such that

Check.

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

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

$$Y_{i+1} := Y_i \bigcup \text{one edge to adjoin every vertex of } X_i^{10}$$

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 $[1/2^i, 1/2^{i-1}]$. ■

Example. Let

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

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

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

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

Lecture 13: Proof of Seifert-Van-Kampen Theorem

4 Feb. 10:00

2.7 Proof of Seifert-Van-Kampen Theorem

Let's start to prove Theorem 2.5.

⁹[HPM02] do this by arguing the union on the right is both open and closed.

¹⁰This is possible if we assume Axiom of Choice.

Proof. The outline of the proof is the following. Let $X = \bigcup_{\alpha} A_{\alpha}$ where A_{α} are open, path-connected and contain the bluepoint 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

$$\alpha|_{s_i, s_{i+1}} =: \alpha_i$$

has image in A_{α_i} for some α_i .¹¹ 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 2.5. 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 some definition.

Definition 2.12 (Factorization). A *factorization* of a homotopy class $[f] \in \pi_1(X, x_0)$ is a formal product

$$[f_1][f_2] \dots [f_{\ell}]$$

with $[f_i] \in \pi_1(A_{\alpha_i}, x_0)$ such that

$$f \simeq f_1 \cdot f_2 \cdot \dots \cdot f_{\ell}.$$

We showed that every $[f]$ has a factorization in step 1 already. Now we want to show that two factorizations

$$[f_1] \cdot \dots \cdot [f_{\ell}] \text{ and } [f'_1] \cdot \dots \cdot [f'_{\ell'}]$$

of $[f]$ must be related by two moves:

¹¹This is a good exercise for point-set topology.

- (a) $[f_i] \cdot [f_{i+1}] = [f_i \cdot f_{i+1}]$ if $[f_i], [f_{i+1}] \in \pi_1(A_\alpha, x_0)$. Namely, the reaction defining the **free product** of groups.
- (b) $[f_i]$ 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 $f_1 \dots f_\ell$ to $f'_1 \dots f'_{\ell'}$, since they both represent $[f]$. We subdivide $I \times I$ into rectangles R_{ij} so that

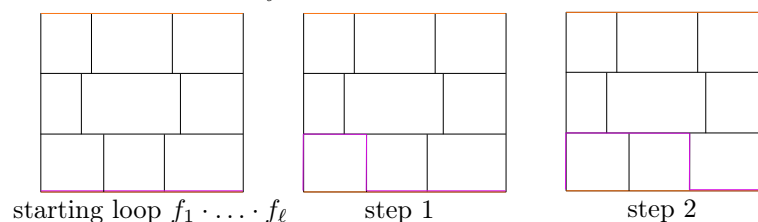
$$F(R_{ij}) \subseteq A_{\alpha_{ij}} =: A_{ij}$$

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}

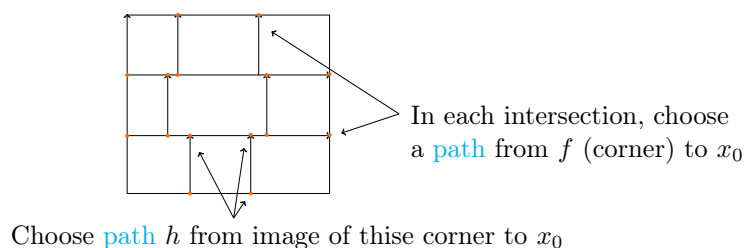
We also argue that we can set up our subdivision so that the partition of the top and bottom intervals must correspond with the two **factorizations** of $[f]$. We then perform our **homotopy** one rectangle at a time.

ending loop $f'_1 \dots f'_{\ell'}$



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.



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 14: Covering Spaces

7 Feb. 10:00

3 Covering Spaces

3.1 Lifting Properties

As always, we start with a definition.

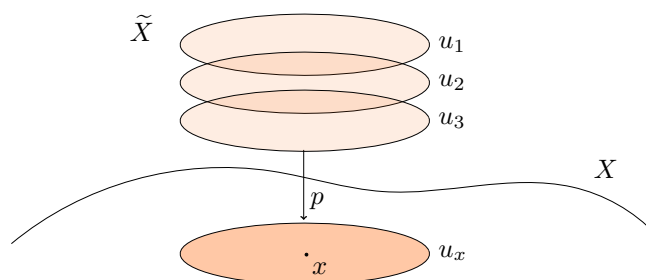
Definition 3.1 (Covering space). A covering space \tilde{X} of X is a space \tilde{X} and a map $p: \tilde{X} \rightarrow X$ such that $\forall x \in X \exists$ neighborhood u_x with $p^{-1}(u_x)$ the disjoint union of open sets

$$\coprod_{\alpha} u_{\alpha}$$

such that

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

is a homeomorphism for every α .



We sometimes call p as covering map.

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

Definition 3.2 (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.

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.

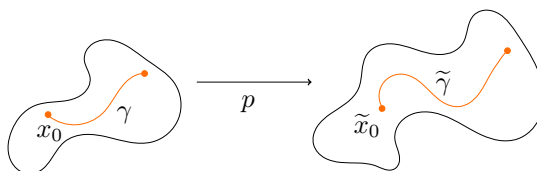
Proposition 3.1 (Homotopy lifting property). The [covering spaces](#) satisfy the [homotopy lifting property](#) such that the following diagram commutes.

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

Proof. We already proved this in homework! ■

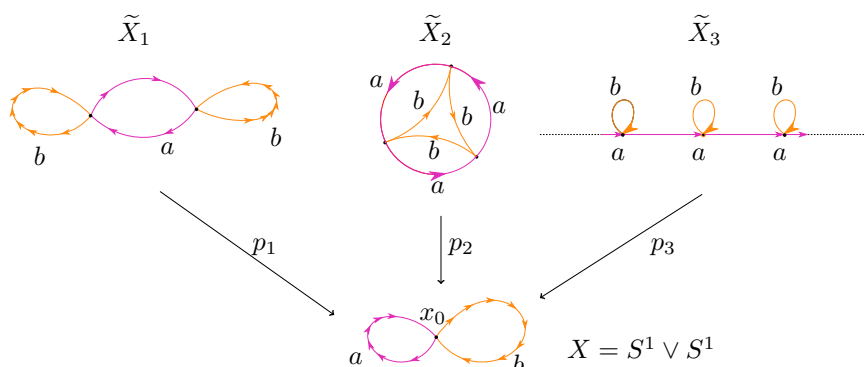
Corollary 3.1. For each [path](#) $\gamma: I \rightarrow X$ in X , $\tilde{x}_0 \in p^{-1}(\gamma(0))$ such that there exists a unique [lift](#) $\tilde{\gamma}$ starting at \tilde{x}_0 .

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 .



Example. Let see some examples.

1. 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 3.2. 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. $p_*(\pi_1(\tilde{X}, \tilde{x}_0)) \subseteq \pi_1(X, x_0) = \{[\gamma] \mid \text{Lift } \tilde{\gamma} \text{ starting at } \tilde{x}_0 \text{ is a loop.}\}$.

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

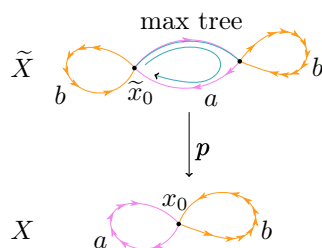
$$\begin{array}{ccc}
 & \tilde{X} & \\
 \nearrow \tilde{\gamma} & & \downarrow p \\
 I & \xrightarrow{\gamma} & X
 \end{array}
 \qquad
 \begin{array}{ccc}
 & \tilde{X} & \\
 \nearrow \tilde{\gamma}_t & & \downarrow p \\
 I \times I & \xrightarrow{\gamma_t} & X
 \end{array}$$

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 3.3 (Lifting criterion). Let $p: (\tilde{Y}, \tilde{y}_0) \rightarrow (Y, y_0)$ be 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

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

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

Lecture 15: Lifting

9 Feb. 10:00

Before proving [Proposition 3.3](#), we first see an application.

Example. Prove that 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 3.3](#). ■

Now we can proof [Proposition 3.3](#).

Proof. 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

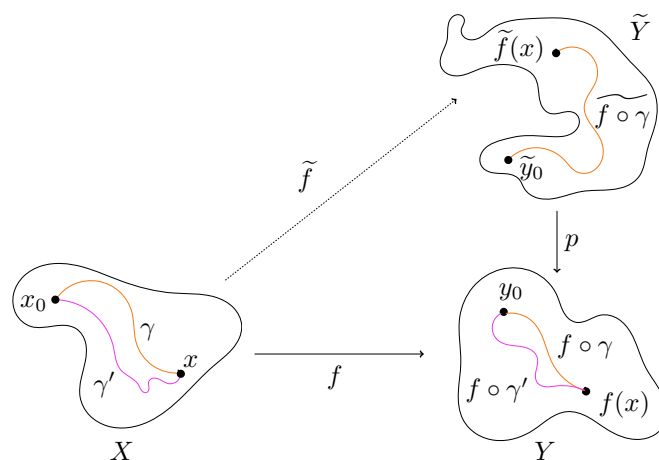
$$\tilde{f}(x) = \tilde{f}\gamma(1).$$

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

$$\widetilde{f\gamma'}(1) = \widetilde{f\gamma}(1).$$

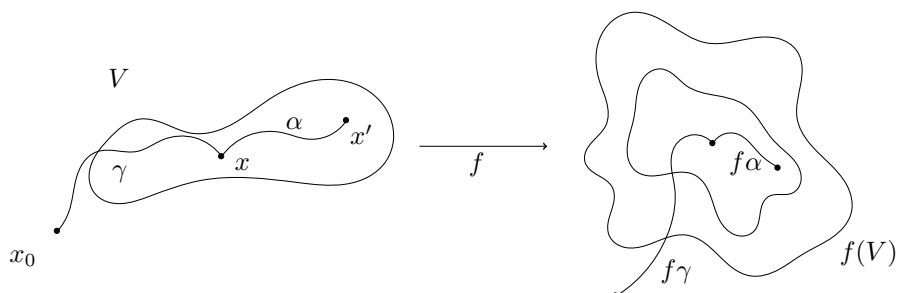
Since $\gamma \cdot \overline{\gamma'}$ is a loop in X at x_0 , we know that $[(f\gamma) \cdot \overline{(f\gamma')}]$ is a class of loops in Y in $\text{Im}(f_*)$. By hypothesis, this class of loops is in $\text{Im}(p_*)$. It [lifts](#) to a loop which is based at \tilde{y}_0 . By uniqueness of [lifts](#), this loop lifting $(f\gamma) \cdot \overline{(f\gamma')}$ to \tilde{Y} must be equal to the [lifts](#) $\widetilde{f\gamma} \cdot \widetilde{\overline{f\gamma'}}$ with a common value at $t = 1/2$. Hence, $\widetilde{f\gamma}(1) = \widetilde{f\gamma'}(1)$ as desired, namely the endpoints agree.



Lecture 16: Proving Proposition 3.3

11 Feb. 10:00

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 so $p|_{\tilde{U}}$ is a 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

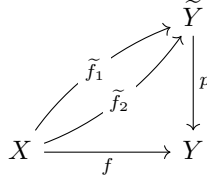
$$\tilde{f}(x') = f\gamma \cdot f\alpha(1) \in \tilde{U},$$

which implies

$$\tilde{f}(V) \subseteq \tilde{U}.$$

■

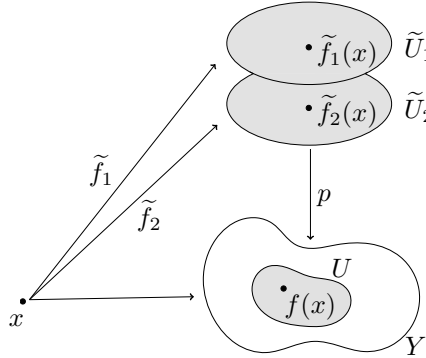
Proposition 3.4. Let $p: \tilde{Y} \rightarrow Y$ be a covering map with X is a connected space. If two lifts \tilde{f}_1, \tilde{f}_2 of the same map f agree at a single point, then they agree everywhere.



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 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 $x \in \text{int}(S)$.

■

3.2 Deck Transformation

We now want to introduce a special kind of transformation.

Definition 3.3 (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 3.4 (Deck transformation). Given a [covering map](#) $p: \tilde{X} \rightarrow X$, the [isomorphisms of covers](#) $\tilde{X} \rightarrow \tilde{X}$ are called *Deck transformation*.

Furthermore, we'll 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

14 Feb. 10:00

Example. Let's see some examples.

1. [Deck transformations](#) $G(\tilde{X})$ are a subgroup of the group of homeomorphisms of \tilde{X} .
2. Given the [cover](#) $p: \mathbb{R} \rightarrow S^1$.
 - [Deck maps](#): translation by $n \in \mathbb{Z}$ units.
 - $G(\mathbb{R}) \cong \mathbb{Z}$
3. Given the [cover](#) $p_n: S^1 \rightarrow S^1$ be an n -sheeted cover.
 - [Deck maps](#): rotation by $2\pi/n$.
 - $G(S^1, p_n) \cong \mathbb{Z} / N\mathbb{Z}$

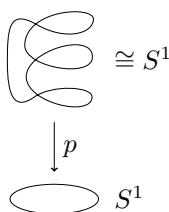


Figure 16: $p: S^1 \rightarrow S^1$ be an N -sheeted cover, where $N = 3$.

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 3.2. 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 3.5 (Regular, Normal). 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

$$\tilde{x}_0 \mapsto \tilde{x}_1.$$



Figure 17: Covers of $S^1 \vee S^1$. 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.

Definition 3.6 (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 3.5. 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

$$H = p_* \left(\pi_1(\tilde{X}, \tilde{x}_0) \right) \subseteq \pi_1(X, x_0).$$

Then

1. p is **normal** if and only if $H \subset \pi_1(X, x_0)$ is **normal**.
2. We have

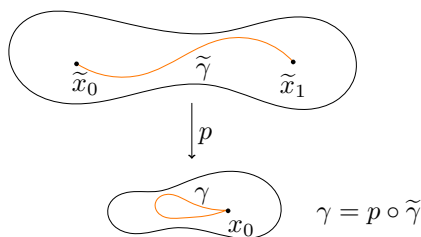
$$G(\tilde{X}) \cong N(H) / H,$$

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}_1 to \tilde{x}_0 . Then

$$p_* \left(\pi_1(\tilde{X}, \tilde{x}_0) \right) = [\gamma]H[\gamma^{-1}]$$

where $H \in \pi_1(\tilde{X}, \tilde{x}_1)$.



Lecture 18: Proving Proposition 3.5

16 Feb. 10:00

Now let's prove Proposition 3.5

Proof. 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.¹² 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, from the result follows directly from the first isomorphism theorem.¹³

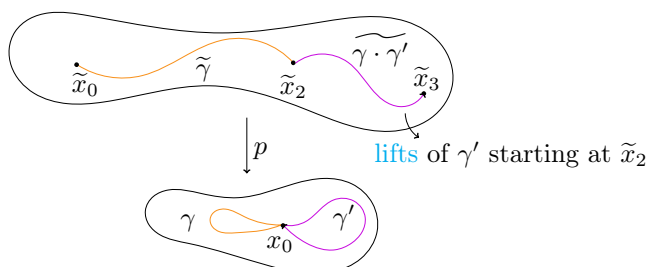
1. We've proved that Φ is surjective before in our work above.
2. $\Phi([\gamma])$ is the identity if and only if τ sends \tilde{x}_0 to \tilde{x}_0 , meaning that $[\gamma]$ lifts to a loop. Then by our characterization of the fundamental group downstairs:

$$\ker(\Phi) = \{[\gamma] \mid [\gamma] \text{ lifts to a loop}\} = H.$$

¹²Alternatively, we can use the lifting criterion.

¹³https://en.wikipedia.org/wiki/Isomorphism_theorems

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 $\tilde{\gamma}_1 \cdot \tau(\tilde{\gamma}_2)$.



It's an exercise to 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 .

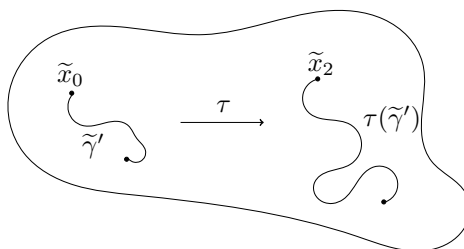


Figure 18: Must be **lift** of γ' starting at \tilde{x}_2

The idea is that by uniqueness of **lifts** we'll have the desired claim. 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 3.3. If p is a **normal covering**, then $G(\tilde{X}) \cong \pi_1(X, x_0) / H$.

Corollary 3.4. 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 Σg be the genus g surface. Prove that Σg has a normal n -sheeted path-connected cover for every n .

Lecture 19: Simplex

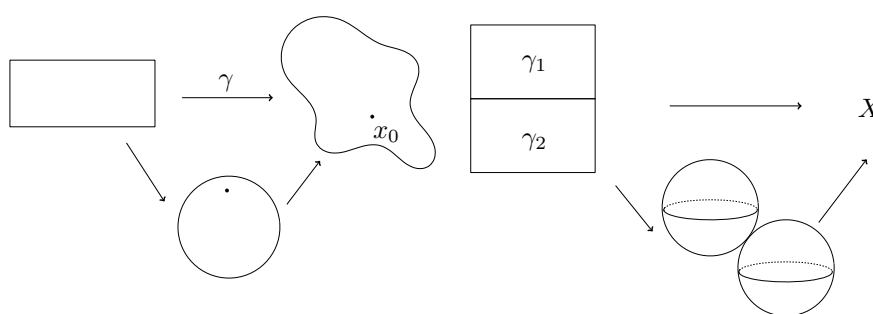
18 Feb. 10:00

4 Homology

4.1 Motivation for Homology

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

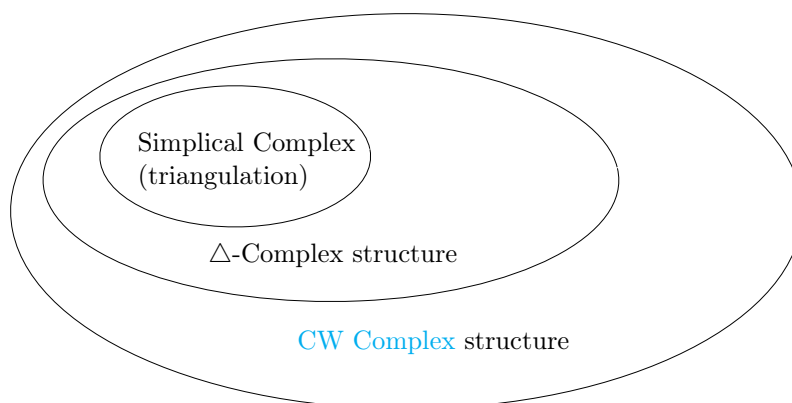
Remark. More like π_n for $n > 1$.

- No basepoints
- Can compute using CW structure.
- Good properties. For example, $H_n = 0$ if $n > \dim X$

4.2 Simplicial Homology

4.2.1 Δ -Simplex

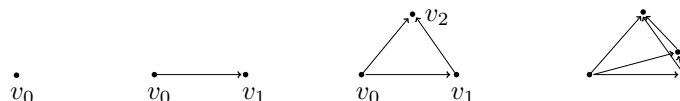
This is a stricter version of a CW complex which allows us to decompose our spaces into cells. In terms of how things fit together, we have the following diagram.



Now we try to give the definition.

Definition 4.1 (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.

Further,

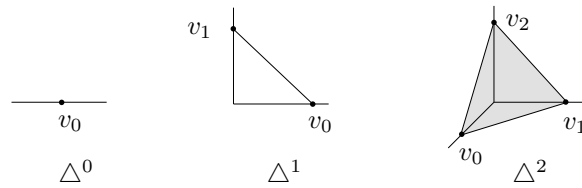
- We can view [simplices](#) as both *combinatorial* and *topological* objects.

An alternative definition can be done.

Definition 4.2 (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 *simplices* will implicitly come with a choice of ordering of the vertices as

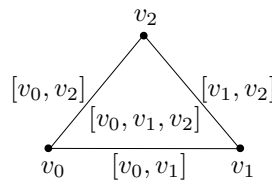
$$\Delta^n = [v_0, v_1, \dots, v_n]$$

such that the convex hull of these points is taken with this ordering.

Lecture 20: Simplicial Complex

21 Feb. 10:00

Definition 4.3 (Subsimplex). A *subsimplex* of a *simplex* σ combinatorially, it's a subset of the vertices; while topologically, it's the convex hull of the subset of vertices.



Definition 4.4 (Face). A *face* of a *simplex* is a *subsimplex* of 1 dimensional lower than Δ^n (codimension 1).

Definition 4.5 (Boundary). The *boundary* $\partial\sigma$ of a *simplex* σ is the union of its *faces*.

Definition 4.6 (Open simplex). The *open simplex* Δ is defined as

$$\mathring{\Delta}^n = \Delta^n / \partial\Delta^n.$$

Definition 4.7 (Δ -Complex). A Δ -complex structure on X is a collection of maps

$$\sigma_\alpha: \Delta^n \rightarrow X$$

such that

1. $\sigma_\alpha|_{\Delta^n}$ 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 Δ^n for all σ_α , i.e., X is a quotient

$$\coprod_{n,\alpha} \Delta^n \xrightarrow{\sigma_\alpha} X.$$

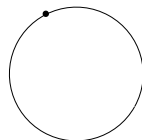
Exercise. A Δ -complex X is a CW complex W characteristic maps σ_α with extra constraints on the attaching maps.

Note. We see that the second condition of Definition 4.7 implies that attaching maps injective on interior of **faces**.

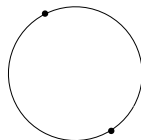
Definition 4.8 (Simplicial complex). A *simplicial complex* is a Δ -complex such that

- 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 **simplex**.

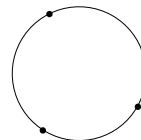
Remark. With Definition 4.8, we see the followings.



Δ -simple
not Simplicial

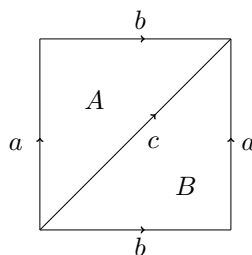


Δ -simple
not Simplicial



Δ -simple
is Simplicial

Example. The torus with the following edges, a, b, c and the gluing in triangles A and B can be seen as follows.



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.

Lecture 21: Homology

23 Feb. 10:00

4.3 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,

$$C_n(X) = \left\{ \text{finite sums } \sum m_\alpha \sigma_\alpha \mid m_\alpha \in \mathbb{Z}, \sigma_\alpha: \Delta^n \rightarrow X \right\}.$$

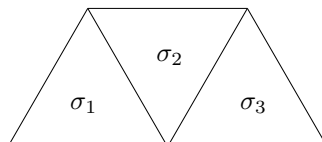
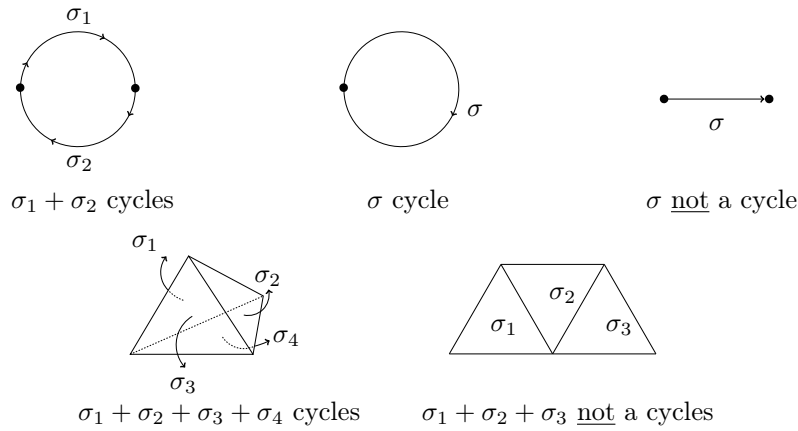


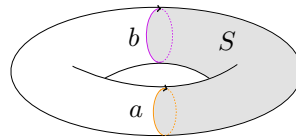
Figure 19: $C_2(X) = \mathbb{Z}\sigma_1 \oplus \mathbb{Z}\sigma_2 \oplus \mathbb{Z}\sigma_3$.

Then, the n -th homology group will be a subquotient of $C_n(X)$, where the heuristic/imprecise idea is

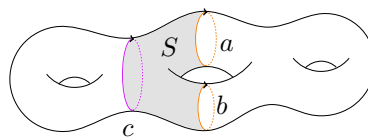
- Take subgroup of C_n of *cycles*. These are sums of [simplices](#) satisfying a combinatorial condition on the boundary gluing maps to ensure that they *close up*, i.e., they have no [boundary](#).



- 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 ($a + b$ ¹⁴ and c are not **homotopic**).



Let's now see the formal definition.

Definition 4.9 (Chain group). We define the *chain group* $C_n(X)$ of order n to be the free Abelian group on the **n -simplices** of X such that

$$C_n(X) := \left\{ \text{finite sums } \sum m_\alpha \sigma_\alpha \mid m_\alpha \in \mathbb{Z}, \sigma_\alpha: \Delta^n \rightarrow X \right\}.$$

¹⁴Which isn't even a loop

Definition 4.10 (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.

Example. We give some lower dimensions examples of [Definition 4.10](#) 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 4.1. For any $n \geq 2$, we have

$$\begin{array}{ccccc} C_n(X) & \xrightarrow{\partial_n} & C_{n-1}(X) & \xrightarrow{\partial_{n-1}} & C_{n-2}(X) \\ & \searrow & \xrightarrow{\partial_{n-1} \circ \partial_n = 0} & & \end{array}$$

Definition 4.11 (Chain complex). A *chain complex* (C_*, d_*) is a collection of maps 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 and group homomorphism such that

$$d_{n-1} \circ d_n = 0.$$

We call C_n the *n-th chain group* and d_n the *n-th differential*.

Remark. We see that

- [Lemma 4.1](#) guarantees that our [simplicial chain groups](#) form a [chain complex](#).
- [Definition 4.11](#) means that $\ker(d_n)$ contains $\text{Im}(d_{n+1})$, since $d_n \circ d_{n+1} = 0$.

Definition 4.12 (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 4.13 (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 spaces X with a **Δ -complex** structure.

Definition 4.14 (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*.

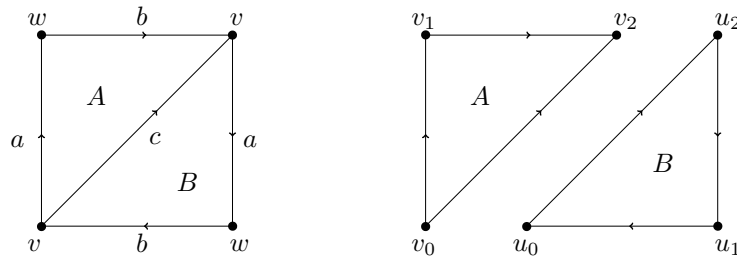
Lecture 22: Calculation of Homology

25 Feb. 10:00

4.4 Calculation of Homology

We start from some calculation about **homology group** of some spaces.

Example. 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

$$\partial_2 : \begin{cases} A & \mapsto b - c + a \\ B & \mapsto -a - c - b \end{cases}, \quad \partial_1 : \begin{cases} a & \mapsto w - v \\ b & \mapsto v - w \\ c & \mapsto v - v = 0 \end{cases}$$

We can also calculate the image and the kernel of C_i , we have

$$\begin{aligned} C_2 : \text{Im} &= 0, & \ker &= 0, \\ C_1 : \text{Im} &= \langle 2c, b - c + a \rangle, & \ker &= \langle b + a, c \rangle, \\ C_0 : \text{Im} &= \langle v, w \rangle, & \ker &= \langle v - w \rangle. \end{aligned}$$

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. Warning! Care is needed when doing *change of bases* over \mathbb{Z} . For example,

$$\mathbb{Z} \langle v, w \rangle \begin{cases} v - w, & \text{if } ; \\ v + w, & \text{if } . \end{cases} \quad \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix}$$

Appendix

References

- [HPM02] A. Hatcher, Cambridge University Press, and Cornell University. Department of Mathematics. *Algebraic Topology*. Algebraic Topology. Cambridge University Press, 2002. ISBN: 9780521795401. URL: <https://books.google.com/books?id=BjKs86kosqC>.