

Algebraic Topology

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1 Bases of the Fundamental Group

1.1 Homotopy equivalence.

Definition 1.1. Let X be a topological space $f, g: X \rightarrow Y$ then we say that f is *homotopic* to g if there is a function $H: X \times I \rightarrow Y$ (called a homotopy) such that

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

Proposition 1.2. *Homotopy is an equivalence relation.*

Lemma 1.3 (Gluing Lemma). *Suppose that $X = A \cup B$ with A, B closed and take $f_1: A \rightarrow Y$, $f_2: B \rightarrow Y$. s.t $f_1(x) = f_2(x)$ for all $x \in A \cap B$. Then*

$$f_3: X \rightarrow Y, \quad f_3(x) = \begin{cases} f_1(x) & \text{if } x \in A \\ f_2(x) & \text{if } x \in B \end{cases}$$

is continuous.

Proof. Let C be a closed set in Y , then

$$\begin{aligned} f_3^{-1}(C) &= f_3^{-1}(C) \cap (A \cup B) \\ &= (f_3^{-1}(C) \cap A) \cup (f_3^{-1}(C) \cap B) \\ &= f_1^{-1}(C) \cup f_2^{-1}(C) \end{aligned}$$

which is closed in X .

□

Example 1.4. Any two function into \mathbb{R}^n (convex set, start shaped set) are homotopic.

Indeed, take two such $f(x), g(x)$ then let

$$H: X \times Y \rightarrow \mathbb{R}^n, \quad H(x, t) = (1 - t)f(x) + tg(x)$$

Note: we call this *the straight line homotopy*.

Relative Homotopy

Definition 1.5. Let $f, g: X \rightarrow Y$ with $A \subseteq X$ and $f|_A = g|_A$ then we say that f is homotopic to g relative to A if there exists a homotopy $H: X \times I \rightarrow Y$ between f and g

$$H(x, t) = f(x) = g(x) \quad \forall t \in I, \forall x \in A$$

Remark 1.6. Homotopy is a special kind of relative homotopy (for $A = \emptyset$).

Proposition 1.7. *Relative homotopy is an equivalence relation.*

Definition 1.8. Let X a topological space and let $x_1, x_2 \in X$ then a path in X going from x_1 to x_2 is a function $\gamma: I \rightarrow X$ s.t

$$\gamma(0) = x_1, \quad \gamma(1) = x_2$$

Definition 1.9. Suppose that γ_1 and γ_2 are two paths in X whose start point and end point coincide, then we say that γ_1 is path homotopic to γ_2 if γ_1 is homotopic to γ_2 relative to $\{0, 1\}$.

Intuitively this means that we can deform γ_1 into γ_2 without moving the endpoints. i.e $H: I \times I \rightarrow X$ s.t

$$H(s, t) = \begin{cases} \gamma_1(s) & \text{if } t = 0 \\ \gamma_2(s) & \text{if } t = 1 \\ \gamma_1(0) = \gamma_2(0) & \text{if } s = 0 \\ \gamma_1(1) = \gamma_2(1) & \text{if } s = 1 \end{cases}$$

Corollary 1.10. *Path homotopy is an equivalence relation.*

Definition 1.11. $\gamma_1, \gamma_2: I \rightarrow X$ with

$$\gamma_1(1) = \gamma_2(0)$$

we define the *product* of these paths to be the path $\gamma_1 \cdot \gamma_2$ given by

$$\gamma_1 \cdot \gamma_2(s) = \begin{cases} \gamma_1(2s) & \text{if } 0 \leq s \leq 1/2 \\ \gamma_2(2s - 1) & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

Note that this is continuous by the Gluing Lemma.

Proposition 1.12. *Path multiplication is compatible with path homotopy; i.e if*

$$\gamma_1 \sim \gamma'_1, \quad \gamma_2 \sim \gamma'_2$$

then

$$\gamma_1 \cdot \gamma_2 \sim \gamma'_1 \sim \gamma'_2$$

Proof. Let $H_1: I \times I \rightarrow X$ and $H_2: I \times I \rightarrow X$ be the corresponding homotopies then define $H: I \times I \rightarrow X$ by

$$H(s, t) = \begin{cases} H_1(2s, t) & \text{if } 0 \leq t \leq 1/2 \\ H_2(2s - 1, t) & \text{if } 1/2 \leq t \leq 1 \end{cases}$$

We have to check that this a valid path homotopy, TODO. \square

1.2 The Fundamental group

Definition 1.13. A loop in X based at x_0 is a path whose end points are both x_0 .

Theorem 1.14. Take X a top space and $x_0 \in X$ then the set of path homotopy equivalence classes of the loops based at x_0 is a group where multiplication, identity and inverses are defined as such:

- $[\gamma_1] \cdot [\gamma_2] = [\gamma_1 \cdot \gamma_2]$
- Identity is $[x_0]$
- Inverse of $[\gamma]$ is $[\bar{\gamma}]$ where

$$\bar{\gamma}(s) = \gamma(1 - s)$$

This group is called the Fundamental group of X based at x_0 denoted by $\pi_1(X, x_0)$.

Remark 1.15. Note that multiplication is well defined, since homotopy behaves nicely with path product.

Lemma 1.16. Let $\varphi: I \rightarrow I$ s.t $\varphi(0) = 0$ and $\varphi(1) = 1$. Then for any path γ we have that

$$\gamma \varphi \sim \gamma$$

we call $\gamma \circ \varphi$ a reparametrization of γ .

Proof. Let $H(s, t) = \gamma((1 - t)s + t\varphi(s))$, then clearly

$$H(s, 0) = \gamma(s), \quad H(s, 1) = \gamma(\varphi(s))$$

$$H(0, t) = \gamma(0), \quad \gamma(1, t) = \gamma(1)$$

\square

Proof of the theorem.

We have to show that this satisfies the axioms of groups:

- **Associativity.** Take $\gamma_1, \gamma_2, \gamma_3: I \rightarrow X$ s.t

$$\gamma_1(1) = \gamma_2(0), \quad \gamma_2(1) = \gamma_3(0)$$

Then we have that

$$(\gamma_1 \cdot \gamma_2) \cdot \gamma_3(s) = \begin{cases} \gamma_1(4s) & \text{if } 0 \leq s \leq 1/4 \\ \gamma_2(4s - 1) & \text{if } 1/4 \leq s \leq 1/2 \\ \gamma_3(2s - 1) & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

and

$$\gamma_1 \cdot (\gamma_2 \cdot \gamma_3)(s) = \begin{cases} \gamma_1(2s) & \text{if } 0 \leq s \leq 1/2 \\ \gamma_2(4s - 2) & \text{if } 1/2 \leq s \leq 3/4 \\ \gamma_3(4s - 3) & \text{if } 3/4 \leq s \leq 1 \end{cases}$$

We want to find $\varphi: I \rightarrow I$ s.t

$$(\gamma_1 \cdot \gamma_2) \cdot \gamma_3(s) = \gamma_1 \cdot (\gamma_2 \cdot \gamma_3)(\varphi(s))$$

Indeed, define

$$\varphi(s) = \begin{cases} 2s & \text{if } 0 \leq s \leq 1/4 \\ s + 1/4 & \text{if } 1/4 \leq s \leq 1/2 \\ 1/2s + 1/2 & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

Check that this is a valid reparametrization; i.e that the equality above holds.

- **Identity.** We will only show left-identity: right is completely analogous. Take $\gamma: I \rightarrow X$, let $x_0 = \gamma(0)$ and $x_0: I \rightarrow X$ s.t $x_0(s) = x_0$. Then

$$x_0 \cdot \gamma(s) = \begin{cases} x_0 = \gamma(0) & \text{if } 0 \leq s \leq 1/2 \\ \gamma(2s - 1) & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

Then clearly $\gamma(\varphi(s)) = x_0 \cdot \gamma(s)$ via

$$\varphi(s) = \begin{cases} 0 & \text{if } 0 \leq s \leq 1/2 \\ 2s - 1 & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

Check that the reparametrization is valid.

- **Inverse.** Suppose that $\gamma: I \rightarrow X$ is a path, fix $\alpha \in I$. Define the path

$$\gamma_\alpha(s) = \gamma(\alpha s)$$

We want to show that

$$\gamma \cdot \bar{\gamma} \sim \gamma(0)$$

Let $H: I \times I \rightarrow X$ be

$$H(s, t) = \gamma_{1-t} \cdot \bar{\gamma}_{1-t}(s)$$

Then notice that

$$H(s, 0) = \gamma_1 \bar{\gamma}_1(s), \quad H(s, 1) = \gamma_0 \cdot \bar{\gamma}_0(s) = \gamma(0)$$

and

$$H(0, t) = \gamma_{1-t}(0) = \gamma(0), \quad H(1, t) = \gamma(0)$$

Where the last equality comes from the fact that

$$H(s, t) = \begin{cases} \gamma_{1-t}(2s) & \text{if } 0 \leq s \leq 1/2 \\ \overline{\gamma_{1-t}}(2s - 1) = \gamma_{1-t}(2 - 2s) = \gamma((1-t)(2-2s)) & \text{if } 1/2 \leq s \leq 1 \end{cases}$$

Note that H is continuous since it is clearly continuous on $[0, 1/2] \times I$ and $[1/2, 1] \times I$ + Gluing lemma.

□

Theorem 1.17. Let X be a topological space and let $x_0, x_1 \in X$; take η a path from $x_0 \rightarrow x_1$. Define $\beta_\eta: \pi_1(X, x_1) \rightarrow \pi_1(X, x_0)$ by

$$\beta_\eta[\gamma] = [\eta \cdot \gamma \cdot \bar{\eta}]$$

Then β_η is an isomorphism.

Proof. • **Well defined.** Let $[\gamma_1] = [\gamma_2]$ then

$$\begin{aligned} [\gamma_1] = [\gamma_2] &\implies \gamma_1 \sim \gamma_2 \\ &\implies \eta \cdot \gamma_1 \sim \eta \cdot \gamma_2 \\ &\implies \eta \cdot \gamma_1 \cdot \bar{\eta} \sim \eta \cdot \gamma_2 \cdot \bar{\eta} \\ &\implies [\eta \cdot \gamma_1 \cdot \bar{\eta}] = [\eta \cdot \gamma_2 \cdot \bar{\eta}] \end{aligned}$$

• **Homomorphism.**

$$\begin{aligned} \beta_\eta([\gamma_1] \cdot [\gamma_2]) &= \beta_\eta([\gamma_1 \cdot \gamma_2]) \\ &= [\eta \cdot \gamma_1 \cdot \gamma_2 \cdot \bar{\eta}] \\ &= [\eta \cdot \gamma_1 \cdot x_1 \cdot \gamma_2 \cdot \bar{\eta}] \\ &= [\eta \cdot \gamma_1 \cdot \bar{\eta}] \cdot [\eta \cdot \gamma_2 \cdot \bar{\eta}] \\ &= \beta_\eta[\gamma_1] \cdot \beta_\eta[\gamma_2] \end{aligned}$$

• **Isomorphism.** Notice that

$$\begin{aligned} \beta_\eta \circ \beta_{\bar{\eta}}[\gamma] &= [\beta_\eta(\bar{\eta}) \cdot \gamma \cdot \eta] \\ &= [\eta \cdot \bar{\eta} \cdot \gamma \cdot \eta \cdot \bar{\eta}] \\ &= [x_0 \cdot \eta \cdot x_0] \\ &= [\gamma] \end{aligned}$$

Similarly $\beta_{\bar{\eta}} \circ \beta_\eta$ is also identity.

□

Corollary 1.18. If X is path connected then $\pi_1(X, x_0)$ is independent of X .

From now on we all space will be path connected (unless stated otherwise explicitly): in this case we will simply write $\pi_1(X)$.

Definition 1.19. If $\pi_1(X) = e$ we say that X is simply connected

Proposition 1.20. X is simply connected $\iff \forall x_0, x_1 \in X$ any two paths between x_0 and x_1 are homotopic.

Proof. \Leftarrow Take $x_0 = x_1$, then any two loops are homotopic, in particular every loop is homotopic to the constant loop.

\Rightarrow Let $x_0, x_1 \in X$ and take $\gamma, \gamma': x_0 \rightarrow x_1$. Note that $\gamma \cdot \bar{\gamma}'$ is a loop, therefore $\gamma \cdot \bar{\gamma}' \sim x_0$. Therefore multiplying both sides by γ' we get

$$\begin{aligned} (\gamma \cdot \bar{\gamma}') \cdot \gamma' &\sim x_0 \cdot \gamma' \\ (\gamma \cdot \bar{\gamma}') &\sim \gamma' \\ \gamma &\sim \gamma' \end{aligned}$$

□

Example 1.21. The following spaces are simply connected

- \mathbb{R}^n : Let γ be a loop based at 0, then let

$$H(s, t) = (1 - t)\gamma(s) + t \cdot x_0 = (1 - t)\gamma(s)$$

- Similarly, every convex set is simply connected.
- Similarly, every star-shaped set is simply connected.
- S^n is simply connected for $n \geq 2$ (proof later).

Notice that S^1 is not simply connected (proof later).

1.3 Homotopy of spaces

Let X, Y be topological spaces and $\varphi: X \rightarrow Y$ be a map. Fix $x_0 \in X$, suppose that γ is a loop based at x_0 , then $\varphi(\gamma)$ is a loop based at $\varphi(x_0)$. Moreover, if $\gamma \sim \gamma'$ via homotopy H , then $\varphi(\gamma) \sim \varphi(\gamma')$ via the homotopy $\varphi \circ H$.

Proof. $H: I \times I \rightarrow X$ s.t

$$H(0, t) = x_0 = H(1, t), \quad H(s, 0) = \gamma(s), \quad H(s, 1) = \gamma'(s)$$

Then

$$\varphi \circ H: I \times I \rightarrow Y$$

and

$$\varphi(H(0, t)) = \varphi(x_0) = \varphi(H(1, t)), \quad H(s, 0) = \varphi(\gamma(s)), \quad \varphi(H(s, 1)) = \varphi(\gamma'(s))$$

□

Therefore we get a well defined map from $\pi(X, x_0)$ to $\pi(Y, \varphi(x_0))$, denote by φ_* and defined by

$$\varphi_*([\gamma]) = [\varphi \circ \gamma]$$

Proposition 1.22. • φ_* is a Homomorphism.

- $(\psi \circ \varphi)_* = \psi_* \circ \varphi_*$.
- $(\mathbb{1})_* = \mathbb{1}_*$
- $\varphi \sim \psi$ relative to x_0 then $\varphi_* = \psi_*$.

Proof. • Take γ_1, γ_2 loops at x_0 , then

$$\varphi(\gamma_1 \cdot \gamma_2) = \varphi(\gamma_1) \cdot \varphi(\gamma_2)$$

because

$$\varphi(\gamma_1 \cdot \gamma_2(s)) = \begin{cases} \varphi(\gamma_1(2s)) & 0 \leq s \leq 1/2 \\ \varphi(\gamma_2(2s - 1)) & 1/2 \leq s \leq 1 \end{cases}$$

but

$$\varphi(\gamma_1) \cdot \varphi(\gamma_2)(s) = \begin{cases} \varphi(\gamma_1(2s)) & 0 \leq s \leq 1/2 \\ \varphi(\gamma_2(2s - 1)) & 1/2 \leq s \leq 1 \end{cases}$$

Therefore

$$\begin{aligned} \varphi_*([\gamma_1] \cdot [\gamma_2]) &= \varphi_*([\gamma_1 \cdot \gamma_2]) \\ &= [\varphi(\gamma_1 \cdot \gamma_2)] = [\varphi(\gamma_1) \cdot \varphi(\gamma_2)] \\ &= [\varphi(\gamma_1)] \cdot [\varphi(\gamma_2)] \\ &= \varphi_*([\gamma_1]) \cdot \varphi_*([\gamma_2]) \end{aligned}$$

- TODO
- TODO
- Let γ be a loop at x_0 and suppose that H is the homotopy between φ and ψ relative to x_0 , therefore $H: X \times I \rightarrow Y$ s.t

$$H(x, 0) = \varphi(x), \quad H(x, 1) = \psi(x), \quad H(x_0, t) = \varphi(x_0) = \psi(x_0)$$

Then consider the map

$$H': I \times I \rightarrow Y, \quad H'(s, t) = H(\gamma(s), t)$$

then

$$H'(s, 0) = H(\gamma(s), 0) = \varphi(\gamma(s)), \quad H'(s, 1) = H(\gamma(s), 1) = \psi(\gamma(s))$$

and

$$H'(0, t) = H(x_0, t) = \varphi(x_0), \quad H'(1, t) = \psi(x_0)$$

Therefore for any γ

$$\varphi_*([\gamma]) = [\varphi(\gamma)] = [\psi(\gamma)] = \psi_*([\gamma])$$

draw the pictures here, it clears things up. □

Corollary 1.23. $X \cong Y \implies \pi_1(X) \cong \pi_1(Y)$.

Proof. Let $\varphi: X \rightarrow Y$, $\psi: Y \rightarrow X$ such that

$$\psi \circ \varphi = \mathbb{1}_X, \quad \varphi \circ \psi = \mathbb{1}_Y$$

Therefore

$$(\psi \circ \varphi)_* = \psi_* \circ \varphi_* = \mathbb{1}_*$$

similarly

$$\varphi_* \circ \psi_* = \mathbb{1}_*$$

Therefore

$$\pi_1(X) \cong \pi_1(Y)$$

□

Remark 1.24. Note that the proof above would still work if we only had that $\psi \circ \varphi \sim \mathbb{1}$ relative to x_0 and $\varphi \circ \psi \sim \mathbb{1}$ relative to $\varphi(x_0)$.

Definition 1.25. Let X, Y be two spaces, we say that X is *homotopic* to Y iff there exists some $\varphi: X \rightarrow Y$ and $\psi: Y \rightarrow X$ such that

$$\psi \circ \varphi \sim \mathbb{1}_X, \quad \varphi \circ \psi \sim \mathbb{1}_Y$$

Proposition 1.26. *Homotopy of spaces is an equivalence relation*

Proof. • **Reflexive.** Take $\varphi = \psi = \mathbb{1}$.

- **Symmetric.** Trivial.
- **Transitive.**

Lemma 1.27. Let $f: X \rightarrow Y$, $f': X \rightarrow Y$ $g, g': Y \rightarrow Z$ with

$$f \sim f', \quad g \sim g'$$

then

$$g \circ f \sim g' \circ f'$$

Proof. Let H be the homotopy between f and f' and H' is the homotopy between g and g' . Then

$$H'': X \times I \rightarrow Z$$

defined by

$$H''(x, t) = H'(H(x, t), t)$$

notice that

$$H''(0, t) = H'(H(x, 0), t) = H'(f(x), t) = g \circ f(x)$$

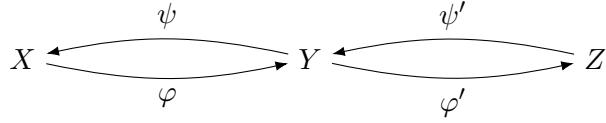
Similarly check the rest. □

Now suppose we have X, Y, Z spaces with

$$\varphi: X \rightarrow Y, \quad \psi: Y \rightarrow Z$$

and

$$\psi: Y \rightarrow X, \quad \psi' Y \rightarrow Z$$



Then

$$\varphi' \circ \varphi: X \rightarrow Z, \quad \psi \circ \psi': Z \rightarrow X$$

s.t

$$\begin{aligned} \psi \circ \psi' \circ \varphi' \circ \varphi &\sim \psi \circ \mathbb{1} \circ \varphi \\ &\sim 1 \end{aligned}$$

□

Terminology. If $X \sim \{\cdot\}$, then we say that X is *contractible*.

Example 1.28. \mathbb{R}^n is contractible; there is only one map $\varphi: \mathbb{R}^n \rightarrow \{\cdot\}$. Take the map $\psi: \cdot \rightarrow \mathbb{R}^n$ to be

$$\cdot \rightarrow 0$$

Indeed

$$\varphi \circ \psi: \cdot \rightarrow \cdot = \mathbb{1}$$

Moreover, $\psi \circ \varphi: \mathbb{R}^n \rightarrow \mathbb{R}^n$

$$\psi \circ \varphi(\alpha) = 0$$

let $H: \mathbb{R}^n \times I \rightarrow \mathbb{R}^n$ defined by

$$H(x, t) = t \cdot x$$

Similarly, we get that any convex subset of \mathbb{R}^n is contractible; any star-shaped set is also contractible.

Later on we will see that S^n is not contractible.

Definition 1.29. Let X be a space and $A \subseteq X$, then $r: X \rightarrow A$ is called a *retraction* iff

$$r|_A = \mathbb{1}|_A$$

In this case we say that A is a *retract* of X .

Example 1.30. • Clearly the function $r: \mathbb{R}^n \rightarrow \{x_0\}$ is a retraction.

- $r: \mathbb{R}^n \setminus \{0\} \rightarrow S^{n-1}, \quad x \rightarrow \frac{x}{|x|}$

Definition 1.31. X a space, $A \subseteq X$: we say that X deformation retracts to A (or that there is a deformation retraction from x to A) (or that A is a deformation retract of X) iff

- There is a retraction $r: X \rightarrow A$.

- Letting $\iota: A \rightarrow X$ be the inclusion map, we have

$$r \circ \iota = \mathbb{1}_{|A}$$

and

$$\iota \circ r \sim \mathbb{1}_{|A} \text{ relative to } A$$

Example 1.32. • \mathbb{R}^n , convex / star shaped subsets deformation retract into a point.

- \mathbb{R}^n deformation retract into D^n : let $r: \mathbb{R}^n \rightarrow D^n$ be defined by

$$r(x) = \begin{cases} x & \text{if } x \in D^n \\ \frac{x}{|x|} & \text{if } x \notin D^n \end{cases}$$

Let $H(x, t) = tr(x) + (1 - t)x$.

- $\mathbb{R}^n \setminus \{0\}$ deformation retracts to S^{n-1} : $r: \mathbb{R}^n \setminus \{0\} \rightarrow S^{n-1}$ by

$$r(x) = \frac{x}{|x|}$$

$H(x, t) = (1 - t)x + t \frac{x}{|x|}$ is the homotopy.

There is no deformation retraction from $\mathbb{R}^n \setminus \{0\}$ to any point.

- $I \times I$ (The closed rectangle) deformation retracts to a cup Exercise.

Proposition 1.33. If X deformation retracts to A and A to B , then X deformation retracts to B .

Proof. Exercise. □

Theorem 1.34. $X \sim Y \implies \pi_1(X) \cong \pi_1(Y)$

Lemma 1.35. Let X, Y topological spaces and $\varphi, \psi: X \rightarrow Y$ be two homotopic functions by a homotopy $H: X \times I \rightarrow Y$. Note that $H(x_0, \cdot)$ is a path in Y (denote it by η). Then the following diagram commutes:

$$\begin{array}{ccc} \pi_1(X, x_0) & \xrightarrow{\psi_*} & \pi_1(Y, \psi(x_0)) \\ \varphi_* \searrow & & \downarrow \beta_\eta \\ & & \pi_1(Y, \varphi(x_0)) \end{array}$$

i.e

$$\beta_\eta \circ \psi_* = \varphi_*$$

Proof of lemma. Let $\gamma: I \rightarrow X$ be a loop based at x_0 , let

$$H'(s, t) = \eta_t(s) \cdot H(\gamma(s), t) \cdot \bar{\eta}_t(s)$$

Convince yourself that the endpoints match here; therefore by the Gluing Lemma H' is continuous.

- At $t = 1$, we get

$$\eta \cdot \psi(\gamma) \cdot \bar{\eta}$$

- At $t = 0$, we get

$$\varphi(x_0) \cdot \varphi(\gamma) \cdot \overline{\varphi(x_0)}$$

So we have that

$$\begin{aligned} \eta \cdot \psi(\gamma) \cdot \bar{\eta} &\sim \varphi(x_0) \cdot \varphi(\gamma) \overline{\varphi(x_0)} \\ &\sim \varphi(\gamma) \end{aligned}$$

and therefore

$$\begin{aligned} [\eta \cdot \psi(\gamma) \cdot \bar{\eta}] &= [\varphi(\gamma)] \\ \beta_\eta[\psi(\gamma)] &= \varphi_*([\gamma]) \\ \beta_\eta(\psi_*([\gamma])) &= \varphi_*([\gamma]) \end{aligned}$$

therefore

$$\varphi_* = \beta_\eta \circ \psi_*$$

□

Proof of the theorem.

$$(Y, y_0) \xrightarrow{\psi} (X, x_0) \xrightarrow{\varphi} (Y, y_1) \xrightarrow{\psi} (X, x_1)$$

we know that

$$\psi \circ \varphi \sim \mathbb{1}, \quad \varphi \circ \psi \sim \mathbb{1}$$

Therefore by the lemma

$$(\psi \circ \varphi)_* = \beta, \quad (\varphi \circ \psi)_* = \beta'$$

But β, β' are isomorphisms, therefore we get that

φ_* is injective and surjective

□

1.4 Fundamental group of all spheres

Theorem 1.36.

$$\pi_1(S^n) = \begin{cases} e & \text{if } n \geq 2 \\ \mathbb{Z} & \text{if } n = 1 \end{cases}$$

Proof. • $\pi_1(S^2)$; there is a homeomorphism between $S^2 \setminus \{N\}$ and \mathbb{R}^2 (N is the North pole) called the stereographic projection. i.e $t \rightarrow (0, 0, 1) + t(x, y, z) = (tx, ty, tx + 1)$ since $1 + tz = 0 \implies t = \frac{t}{1-z}$ we get the map Σ given by

$$\Sigma(x, y, z) = \left(\frac{x}{1-z}, \frac{y}{1-z} \right)$$

For the inverse map $t \rightarrow (0, 0, 1) + t(\alpha, \beta, -1) = (t\alpha, t\beta, 1-t)$; on the sphere

$$t^2\alpha^2 + t^2\beta^2 + (1-t)^2 = 1 \implies t = \frac{2}{\alpha^2 + \beta^2 + 1}$$

so its inverse is given by

$$\Sigma^{-1}\left(\frac{2}{\alpha^2 + \beta^2 + 1}, \frac{2\beta}{\alpha^2 + \beta^2 + 1}, 1 - \frac{2}{\alpha^2 + \beta^2 + 1}\right)$$

TODO, do the same for \mathbb{R}^n .

We shall take our loops to be based at the south pole S . Let $\gamma: I \rightarrow S^2$ be such a loop. If it happens that γ never passes through N ; $\Sigma \circ \gamma$ is a loop in \mathbb{R}^2 based at 0. Thus $H: I \times I \rightarrow S^2$ given by

$$H(s, t) = \Sigma^{-1}((1-t)\Sigma \circ \gamma(s))$$

gives a homotopy between γ and the constant loop at the south pole.

Now suppose that we have any loop $\gamma: I \rightarrow S^2$. Consider the preimage by γ of the open Northern hemisphere, this is open in I since γ is continuous; in fact it is open in $(0, 1)$ (and hence an open subset of \mathbb{R}). Now any open subset of \mathbb{R} is the union of countably many disjoint open intervals. Consider now the preimage of N , it must be closed in $[0, 1]$ and hence must be compact. Therefore since the preimage of the open Northern hemisphere contains that of N ; the preimage of N is an open cover of the preimage of N . So it has a finite subcover. Thus there are finitely many disjoint open intervals which contain the preimage of N . Consider one of these intervals (a, b) . Note that $\gamma((a, b)) \subseteq N$; since γ is continuous we can conclude that $\gamma(a), \gamma(b) \in \bar{N}$ (the closed Northern hemisphere). Note that $\gamma(a), \gamma(b)$ must be on the equator; since if they were in the Northern hemisphere we would have that a belongs to one of the other *disjoint* intervals to (a, b) . Note that the closed Northern hemisphere is homeomorphic to D^2 by $(x, y, z) \rightarrow (x, y)$. but note that $\partial D^2 = S^1$ which is path connected; since we can find some path $\eta: I \rightarrow S^1$ going from $\gamma(a) \rightarrow \gamma(b)$ with η homotopic $\gamma|_{[a,b]}$.

Now we can write a homotopy between γ and some loop that skips N ; see the picture we are using the homotopy above on all (a, b) like above. This is continuous by the gluing lemma according to our homotopy. So γ is homotopic to a loop that skips N and so homotopic to the constant loop.

- We will think of S^1 as

$$\{z \in \mathbb{C}: |z| = 1\}$$

We will base our loops at the point $z = 1$. We define

$$\Phi: \mathbb{Z} \rightarrow \pi_1(S^1), \quad \Phi(n) = [e^{2\pi ins}]$$

We also define

$$p: \mathbb{R} \rightarrow S^1, \quad p(x) = e^{2\pi ix}$$

Note that $[p(ns)] = \Phi(n)$. We will show that Φ is a homomorphism

$$\begin{aligned}\Phi(n) \cdot \Phi(m) &= [p(ns)] \cdot [p(ms)] \\ &= [p(ns) \cdot p(ms)] \\ &= [p(ns) \cdot p(n + ms)] \\ &= [p(ns \cdot (n + ms))]\end{aligned}$$

Note that $ns \cdot (n + ms)$ is a path $0 \rightarrow m + n$, but \mathbb{R} is simply connected, hence

$$ns \cdot (n + ms) \sim (n + m)s \implies p(ns \cdot (n + ms)) \sim p((n + m) \cdot s)$$

Therefore

$$\Phi(n) \cdot \Phi(m) = [p(n + m)s] = \Phi(n + m)$$

Claim 1. For any path γ in S^1 starting at 1, there is a unique path $\tilde{\gamma} \in \mathbb{R}$ starting at 0, s.t

$$p(\tilde{\gamma}) = \gamma$$

we say that $\tilde{\gamma}$ is the *lift* of γ starting at 0.

Claim 2. Suppose that γ_1, γ_2 are two paths in S^1 starting at 1, which are homotopic. Then their lifts starting at 0 are also homotopic.

Φ is surjective. Let $[\gamma] \in \pi_1(S^1)$, then we know that there is a unique $\tilde{\gamma}$ in \mathbb{R} s.t

$$\tilde{\gamma}(0) = 0, \quad p(\tilde{\gamma}) = \gamma$$

Especially $p(\tilde{\gamma}(1)) = \gamma(1) = 1$, hence

$$\tilde{\gamma}(1) = n \in \mathbb{Z} \implies \tilde{\gamma} \sim ns$$

Therefore

$$p(\tilde{\gamma}) \sim p(ns) \implies \gamma \sim p(ns) \implies [\gamma] = [p(ns)] = \Phi(n)$$

Φ is injective. Suppose that $\Phi(n) = \Phi(m)$ therefore

$$[p(ns)] = [p(ms)]$$

We have that the lift of $p(ns)$ is ns and the lift of $p(ms)$ is ms but

$$p(ns) \sim p(ms) \implies ns \sim ms \implies n = m$$

We will prove the two claims in the following setting: \tilde{X}, X two spaces, $p: \tilde{X} \rightarrow X$ s.t $\forall p \in X, \exists U \ni p$ open then $p^{-1}(U)$ is a disjoint union of open sets s.t each one of them (say V) satisfies

$$p|_V \text{ is a homeomorphism onto } U$$

Such a U is called an elementary neighborhood or an evenly covered neighborhood. p is called the projection covering map and

(\tilde{X}, p) is called a covering space of X

The example to take in mind here is $X = S^1$, $\tilde{X} = \mathbb{R}$ with p "wrapping" \mathbb{R} around S^1 . Indeed consider $U_1 = S^1 \setminus \{1\}$, then $p^{-1}(U_1) = \mathbb{R} \setminus \mathbb{Z}$; and $U_2 = S^1 \setminus \{-1\}$ then $p^{-1}(U_2)$ and $U_2 = \mathbb{R} \setminus (1/2\mathbb{Z})$, so (\mathbb{R}, p) is indeed a covering space of S^1 .

Claim 3. Suppose that (\tilde{X}, p) is a covering space of X , and let $f: Y \times I \rightarrow X$ and suppose we have some $\tilde{f}: Y \times \{0\} \rightarrow \tilde{X}$ s.t

$$p \circ \tilde{f} = f$$

then \tilde{f} can be extended *uniquely* to $Y \times I$ s.t $p \circ \tilde{f} = f$ (draw the picture).

Proof that claim 3 implies claim 1 and 2. For claim 1, let $Y = \{\cdot\}$, in this case

$$\{\cdot\} \times I \cong I$$

so we have that $f: I \rightarrow X$ and $\tilde{f}: 0 \rightarrow \tilde{X}$ s.t \tilde{f} can be uniquely extended to I ; which is precisely claim 1 where we are given a path in X and the starting point of the lift is \tilde{X} . For claim 2, take $Y = I$ and f to be the homotopy between the two paths in X ; from claim 1 we can lift the homotopy at the initial time; claim 3 lifts the homotopy to \tilde{X} . By uniqueness of lifts the sides of the homotopy lift to the constant paths and the top of the homotopy gives a lift of the second path starting where the lift of the first path started.

Proof of claim 3. Let $y \in Y$, $\forall t \in I$ there is an open neighborhood O_t of t in I and an open neighborhood N_t of y in Y s.t

$$f(N_t \times O_t) \subseteq \text{an elementary neighborhood}$$

$\{y\} \times I$ is compact and $\{N_t \times O_t\}_{t \in I}$ is an open cover, therefore $\exists t_1, \dots, t_k \in I$ s.t

$$\{y\} \times I \subseteq (N_{t_1} \times O_{t_1}) \cup \dots \cup (N_{t_k} \times O_{t_k})$$

Let $N = \bigcap_{i=1}^k N_{t_i}$, and let $\delta > 0$ be the Lebesgue number of the cover O_{t_1}, \dots, O_{t_k} . Therefore any closed interval of length $\leq \delta$ is contained in one of the O_t 's. Consider $N \times [0, \delta]$ we know that $f(N \times [0, \delta]) \subset U$ an elementary neighborhood. But $p \circ \tilde{f} = f$, therefore $\tilde{f}(N \times 0) \subset p^{-1}(U)$, let \tilde{U} be the "part" of $p^{-1}(U)$ which contains $\tilde{f}(y, 0)$. Now by taking the preimage of \tilde{U} by \tilde{f} we get some open subset of Y which is also an open subset of N ; replace N with this smaller subset call it N . Now p is a homeomorphism between \tilde{U} and U , so it has an inverse $p^{-1}: U \rightarrow \tilde{U}$, define

$$\tilde{f} = p^{-1} \circ f$$

This way, we have extended \tilde{f} to $N \times [0, \delta]$. Now do the same for $N \times [\delta, 2\delta]$ by looking at $\tilde{f}(N \times \{\delta\})$ and making sure that it maps to only one of the preimages of the new elementary neighborhood, we shrink N again and extend \tilde{f} by letting it be $p^{-1} \circ f$.

Note that by construction we have that $p \circ \tilde{f} = f$, and it is continuous by the Gluing lemma. Hence we know that $\forall y \in Y, \exists N_y$ s.t \tilde{f} is extended continuously to include $N_y \times I$ with $p \circ \tilde{f} = f$. Let us show that lifts of paths are unique; indeed suppose that we have $\gamma: I \rightarrow X$ a path in X , and let $\tilde{\gamma}_1, \tilde{\gamma}_2$ be two lifts of γ (i.e $p \circ \tilde{\gamma}_1 = p \circ \tilde{\gamma}_2 = \gamma$ and they both have the same start point). Therefore $\exists \delta > 0$ s.t any closed interval of length δ is mapped by γ into an elementary neighborhood. Consider the interval $[0, \delta]$, we know that

$$\gamma([0, \delta]) \subset \text{an elementary neighborhood } U$$

This implies that $\tilde{\gamma}_1([0, \delta]) \subset p^{-1}(U)$ and $\tilde{\gamma}_2([0, \delta]) \subset p^{-1}(U)$; since $[0, \delta]$ is connected, we know that

$$\tilde{\gamma}_1([0, \delta]), \tilde{\gamma}_2([0, \delta]) \subset \text{a single } \tilde{U}_1, \tilde{U}_2$$

since $\tilde{\gamma}_1(0) = \tilde{\gamma}_2(0)$ we get $\tilde{U}_1 = \tilde{U}_2$. But since $p \circ \tilde{\gamma}_1 = p \circ \tilde{\gamma}_2$ and since p is a homeomorphism, then

$$\tilde{U}_1 = \tilde{U}_2 \rightarrow 0$$

Proceeding similarly, we get that $\tilde{\gamma}_1 = \tilde{\gamma}_2$.

Note that restricting f to a line like $\{y\} \times I$ gives a path in X , and restricting \tilde{f} to this line gives us a lift of this path. So if we use \tilde{f} 's coming from different $N_y \times I$'s, then they must coincide on the intersection because the intersection is made of lines as above. So \tilde{f} and \tilde{f} is unique. And \tilde{f} is continuous using the gluing lemma for open sets.

□

Theorem 1.37 (Fundamental theorem of Algebra). *Let $p(z) = z^n + a_{n-1}z^{n-1} + \cdots + a_0$ then*

$$p(z_0) = 0 \text{ for some } z_0 \in \mathbb{C}$$

Proof. Assume that $p(z) \neq 0$ consider

$$H_1(s, t) = \frac{\frac{p(re^{2\pi is})}{|p(re^{2\pi is})|}}{\frac{p(tr)}{|p(tr)|}}$$

Note that this gives a homotopy between the constant loop in S^1 at 1 and $\frac{p(re^{2\pi is})}{|p(re^{2\pi is})|}$. Choose $r > 0$ to be s.t $r > 1$ and $r > |a_{n-1}| + \cdots + |a_0|$, then notice that if z is restricted to the circle of radius r , we have that

$$\begin{aligned} |z|^n &= r^n = r^{n-1} \cdot r > r^{n-1}(|a_{n-1}| + \cdots + |a_0|) \\ &> r^{n-1}|a_{n-1}| + \cdots + r^{n-1}|a_0| \\ &> r^{n-1}|a_{n-1}| + r^{n-2}|a_{n-2}| + \cdots + |a_0| \\ &= |a_{n-1}z^{n-1}| + \cdots + |a_0| \\ &\geq |a_{n-1}z^{n-1}| + \cdots + |a_0| \end{aligned}$$

it follows that the following polynomials depending on t never vanish on the circle of radius r :

$$q_t(z) = z^n + t(a_{n-1}z^{n-1} + \cdots + a_0)$$

This is because for $|z| = r$ we have that

$$q_t(z) \geq |z^n| - |t(a_{n-1}z^{n-1} + \cdots + a_0)| > 0$$

Now consider $H_2(s, t)$ to be

$$H_2(s, t) = \frac{\frac{q_t(re^{2\pi i s})}{|q_t(re^{2\pi i s})|}}{\frac{q_t(r)}{|p(r)|}}$$

Note that this gives a homotopy between the loop which we just created (write it out TODO); and

$$\frac{\frac{r^n e^{2\pi i ns}}{r^n}}{r^n/r^n} = e^{2\pi i ns}$$

Therefore using both H_1 and H_2 we have a homotopy between the constant loop and $e^{2\pi i ns}$ by contradiction. \square

Theorem 1.38 (Brouwer's fixed point). $f: D^n \rightarrow D^n$ then f has a fixed point, i.e $\exists p_0 \in D^n$ s.t

$$f(p_0) = p_0$$