

11 | Excision

One of the main properties of homology groups is excision. It can be stated as follows:

11.1 Theorem. *Let X be a space and $X_1, X_2 \subseteq X$ be sets such that $X = \text{Int } X_1 \cup \text{Int } X_2$ where $\text{Int } X_i$ is the interior of X_i in X . Then the map of pairs $i: (X_1, X_1 \cap X_2) \rightarrow (X, X_2)$ induces an isomorphism*

$$i_*: H_n(X_1, X_1 \cap X_2) \xrightarrow{\cong} H_n(X, X_2)$$

for all $n \geq 0$.

The same property does not hold in general for homotopy groups. However, it does hold under some extra assumptions. In order to make this precise we will need a definition.

11.2 Definition. Let $A \subseteq X$ and let $0 \leq n \leq \infty$. The pair (X, A) is *n-connected* if the map $\pi_0(A) \rightarrow \pi_0(X)$ is onto and $\pi_k(X, A, x_0) = \{1\}$ for all $x_0 \in A$ and all $1 \leq k \leq n$.

11.3 Proposition. *Let $A \subseteq X$. The following conditions are equivalent.*

- 1) (X, A) is *n-connected*.
- 2) The homomorphism $i_*: \pi_k(A, x_0) \rightarrow \pi_k(X, x_0)$ induced by the inclusion map $i: A \hookrightarrow X$ is an isomorphism for all $x_0 \in A$ and all $k < n$ and it is an epimorphism for $k = n$.
- 3) For $k \leq n$, any map $(I^k, \partial I^k) \rightarrow (X, A)$ is homotopic relative to ∂I^k to a map $I^k \rightarrow A$.

Proof. Exercise. □

11.4 Excision Theorem. *Let X be a space and $X_1, X_2 \subseteq X$ be open sets such that $X = \text{Int } X_1 \cup \text{Int } X_2$ where $\text{Int } X_i$ is the interior of X_i in X . Assume that*

- $(X_1, X_1 \cap X_2)$ is *m-connected*
- $(X_2, X_1 \cap X_2)$ is *n-connected*

for some $m, n \geq 0$. Then for any $x_0 \in X_1 \cap X_2$ the homomorphism

$$i_*: \pi_k(X_1, X_1 \cap X_2, x_0) \rightarrow \pi_k(X, X_2, x_0)$$

induced by the inclusion map, is an isomorphism for $1 \leq k < m + n$ and it is onto for $k = m + n$.

In this chapter we will explore some consequences Theorem 11.4, and we will return to its proof in Chapter 13.

11.5 Proposition. Let (X, A) be a pair with the homotopy extension property and let $q: X \rightarrow X/A$ be the quotient map. Let $x_0 \in A$ and $* = q(A) \in X/A$. If (X, A) is m -connected and the space A is n -connected for some $m, n \geq 0$ then the homomorphism

$$q_*: \pi_k(X, A, x_0) \rightarrow \pi_k(X/A, *, *) = \pi_k(X/A, *)$$

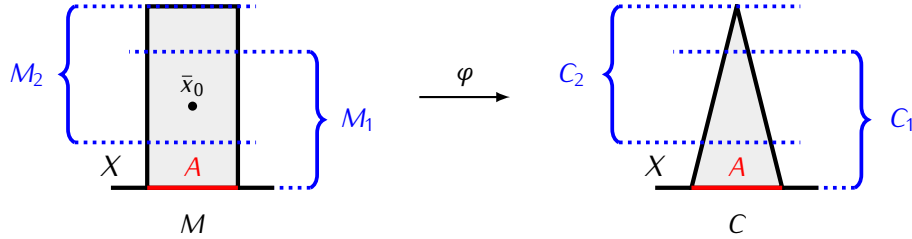
is an isomorphism for $k \leq m + n$ and it is an epimorphism for $k = m + n + 1$.

Proof. Let $j: A \hookrightarrow X$ be the inclusion map. Let M denote the mapping cylinder of j :

$$M = (A \times [0, 1] \sqcup X) / \sim$$

where $(x, 0) \sim x$ for all $x \in A$. Also, let $C = M/(A \times \{1\})$ be the mapping cone of j . In other words, C is obtained by attaching the cone $CA = A \times [0, 1]/(A \times \{1\})$ to X .

Take the quotient map $\varphi: M \rightarrow C$. Denote by $M_1, M_2 \subseteq M$ the subspaces of M given by $M_1 = X \cup A \times [0, \frac{3}{4}]$ and $M_2 = A \times [\frac{1}{4}, 1]$, and let $C_i = \varphi(M_i)$ for $i = 1, 2$. Also, let $\bar{x}_0 = (x_0, \frac{1}{2}) \in M_1 \cap M_2$.



Let $r: M \rightarrow X$ be the retraction map, and let $s: C \rightarrow X/A$ be the map that sends the cone $CA \subseteq C$ to the point $* \in X/A$. Both r and s are homotopy equivalences. For s this follows from Proposition 2.15 using the fact that since (X, A) has the homotopy extension property, then (C, CA) also has this property.

For any $k \geq 1$ the following diagram commutes:

$$\begin{array}{ccc}
\pi_k(X, A, x_0) & \xrightarrow{q_*} & \pi_k(X/A, *, *) \\
\uparrow r_* \cong & & \uparrow \cong s_* \\
\pi_k(M, M_2, \bar{x}_0) & \xrightarrow{\varphi_*} & \pi_k(C, C_2, \varphi(\bar{x}_0)) \\
\uparrow i_* \cong & & \uparrow i'_* \\
\pi_k(M_1, M_1 \cap M_2, \bar{x}_0) & \xrightarrow[k_* \cong]{} & \pi_k(C_1, C_1 \cap C_2, \varphi(\bar{x}_0))
\end{array}$$

The homomorphisms i_* , i'_* and k_* are induced by inclusions. Since $i: (M_1, M_1 \cap M_2) \rightarrow (M, M_1 \cap M_2)$ is a homotopy equivalence and $k: (M_1, M_1 \cap M_2) \rightarrow (C_1, C_1 \cap C_2)$ is a homeomorphism, i_* and k_* are isomorphisms. It follows that q_* is an isomorphism or epimorphism if and only if i'_* has the same property.

From the above diagram we also obtain that $\pi_k(C_1, C_1 \cap C_2, \varphi(\bar{x}_0)) \cong \pi_k(X, A, x_0)$ for all k , so $(C_1, C_1 \cap C_2)$ is m -connected. Also, since C_2 is a contractible space, from the long exact sequence of the pair $(C_2, C_1 \cap C_2)$ we get

$$\pi_k(C_2, C_1 \cap C_2, \varphi(\bar{x}_0)) \cong \pi_{k-1}(C_1 \cap C_2, \varphi(\bar{x}_0)) \cong \pi_{k-1}(A, x_0)$$

Since by assumption A is n -connected, thus $(C_2, C_1 \cap C_2)$ is $(n+1)$ -connected. By the Excision Theorem 11.4 we obtain that i'_* (and thus also q_*) is an isomorphism for $k \leq m+n$ and an epimorphism for $k = m+n+1$. \square

Let (X, x_0) be a pointed space and let $\omega: (I^n, \partial I^n) \rightarrow (X, x_0)$ represent an element $[\omega] \in \pi_n(X, x_0)$. Let ΣX be the reduced suspension of X . Consider the map $\Sigma'\omega: I^{n+1} \rightarrow \Sigma X$ obtained the composition

$$\Sigma'\omega: I^{n+1} = I^n \times [0, 1] \xrightarrow{q} \Sigma I^n \xrightarrow{\Sigma\omega} \Sigma X$$

where q is the quotient map. One can check that $\Sigma'\omega$ represents an element of $\pi_{n+1}(\Sigma X, \bar{x}_0)$.

11.6 Definition/Proposition. The assignment $[\omega] \mapsto [\Sigma'\omega]$ defines a homomorphism of groups

$$\Sigma_*: \pi_n(X, x_0) \rightarrow \pi_{n+1}(\Sigma X, \bar{x}_0)$$

which is called the *suspension homomorphism*.

Proof. The function Σ_* is well defined since the suspension functor preserves homotopy classes of maps. It remains to check that Σ_* is a group homomorphism (exercise). \square

11.7 Freudenthal Suspension Theorem. Let (X, x_0) be a well-pointed, n -connected space. Let \bar{x}_0 denote the basepoint in the reduced suspension ΣX . The suspension homomorphism

$$\Sigma_*: \pi_k(X, x_0) \rightarrow \pi_{k+1}(\Sigma X, \bar{x}_0)$$

is an isomorphism for $k \leq 2n$ and it is an epimorphism for $k = 2n + 1$.

Proof. First, let $CX = X \times [0, 1]/X \times \{1\}$ be the cone on X . Identifying X with $X \times \{0\}$ we can consider it as a subspace of CX . Since CX is a contractible space, in the long exact sequence of the pair (CX, X) the homomorphism $\partial: \pi_{k+1}(CX, X, x_0) \rightarrow \pi_k(X, x_0)$ is an isomorphism for all $k \geq 0$. Let ∂^{-1} be the inverse isomorphism.

One can check (exercise) that if (X, x_0) is a well-pointed space, then for any $k \geq 0$ the following diagram commutes:

$$\begin{array}{ccc} \pi_k(X, x_0) & \xrightarrow{\Sigma_*} & \pi_{k+1}(\Sigma X, \bar{x}_0) \\ \partial^{-1} \downarrow \cong & & \cong \uparrow q'_* \\ \pi_{k+1}(CX, X, x_0) & \xrightarrow{q_*} & \pi_{k+1}(CX/X, \bar{x}_0) \end{array}$$

Here q_* and q'_* are induced by the quotient maps $q: CX \rightarrow CX/X$ and $q': CX/X = SX \rightarrow \Sigma X$.

Since (X, x_0) is well-pointed, the map q' is a homotopy equivalence, and thus q'_* is an isomorphism. It follows that Σ_* is an isomorphism or epimorphism if and only if this holds for q_* . Since X is n -connected and CX is contractible, the pair (CX, X) is $n + 1$ -connected. Therefore, by Proposition 11.5, q_* is an isomorphism for $k + 1 \leq 2n + 1$ (or $k \leq 2n$) and an epimorphism for $k + 1 = 2n + 2$ (i.e. $k = 2n + 1$)

□

Since the sphere S^n is $(n - 1)$ -connected, by Theorem 11.7 we obtain:

11.8 Corollary. *The suspension homomorphism*

$$\Sigma_*: \pi_k(S^n) \rightarrow \pi_{k+1}(\Sigma S^n) \cong \pi_{k+1}(S^{n+1})$$

is an isomorphism for $k \leq 2n - 2$ and an epimorphism for $k = 2n - 1$.

11.9 Corollary. *For any $n \geq 1$ we have $\pi_n(S^n) \cong \mathbb{Z}$.*

Proof. We argue by induction with respect to n . We already know that $\pi_1(S^1) \cong \mathbb{Z}$. Also, by Theorem 7.26 we have $\pi_2(S^2) \cong \mathbb{Z}$.

Next, assume that $\pi_n(S^n) \cong \mathbb{Z}$ for some $n \geq 2$. In such case $2n - 2 \geq n$, so by Corollary 11.8 we obtain $\mathbb{Z} \cong \pi_n(S^n) \cong \pi_{n+1}(S^{n+1})$. □

11.10 Note. 1) By Corollary 11.8 the suspension homomorphism $\Sigma_*: \pi_n(S^n) \rightarrow \pi_{n+1}(S^{n+1})$ is an isomorphism for all $n \geq 2$. By the same corollary $\Sigma_*: \pi_1(S^1) \rightarrow \pi_2(S^2)$ is onto, and since every epimorphism $\mathbb{Z} \rightarrow \mathbb{Z}$ is an isomorphism, it follows that this is an isomorphism as well.

2) The generator of the group $\pi_n(S^n)$ is represented by the identity map $\text{id}: S^n \rightarrow S^n$. For $n = 1$ it follows from the direct computation of $\pi_1(S^1)$, and for $n > 1$ it holds since the suspension isomorphism maps the homotopy class of $\text{id}_{S^{n-1}}$ to the homotopy class of id_{S^n} .

11.11 Corollary. $\pi_3(S^2) \cong \mathbb{Z}$ and the generator of $\pi_3(S^2)$ is given by the homotopy class of the Hopf bundle map (7.25).

Proof. The long exact sequence of the Hopf fibration $S^1 \rightarrow S^3 \xrightarrow{p} S^2$ gives an exact sequence:

$$0 = \pi_3(S^1) \longrightarrow \pi_3(S^3) \xrightarrow{p_*} \pi_3(S^2) \xrightarrow{\partial} \pi_2(S^1) = 0$$

Therefore p_* is an isomorphism and so $\pi_3(S^2) \cong \pi_3(S^3) \cong \mathbb{Z}$. Also, since $[\text{id}_{S^3}]$ is a generator of $\pi_3(S^3)$, thus $p_*([\text{id}_{S^3}]) = [p]$ is a generator of $\pi_3(S^2)$. \square

11.12 Note. Notice that since $\pi_2(S^1) = 0$, the suspension homomorphism $\Sigma_*: \pi_2(S^1) \rightarrow \pi_3(S^2)$ is not an isomorphism.

11.13 Corollary. For $n \geq 1$ the group $\pi_{n+1}(S^n)$ is cyclic.

Proof. We have $\pi_2(S^1) = 0$ and $\pi_3(S^2) \cong \mathbb{Z}$. By Corollary 11.8 the suspension homomorphism $\mathbb{Z} \cong \pi_3(S^2) \rightarrow \pi_4(S^3)$ is onto, so $\pi_4(S^3)$ is a cyclic group. By the same corollary we have $\pi_{n+1}(S^n) \cong \pi_{n+2}(S^{n+1})$ for all $n \geq 3$. \square