

14 | Weak Equivalences

14.1 Definition. Let $0 \leq n \leq \infty$. A map $f: X \rightarrow Y$ is an n -equivalence if the induced homomorphism $f_*: \pi_i(X, x_0) \rightarrow \pi_i(Y, f(x_0))$ is an isomorphism for $0 \leq i < n$ and it is an epimorphism for $i = n$ for all $x_0 \in X$. A map f is a *weak (homotopy) equivalence* if it is an ∞ -equivalence.

Recall that for a map $f: X \rightarrow Y$ the mapping cylinder of f is the space

$$M_f = (X \times [0, 1] \sqcup Y) / \sim$$

where $(x, 0) \sim f(x)$ for all $x \in X$. We will consider X as a subspace of M_f by identifying it with $X \times \{1\}$.

14.2 Proposition. Given a map $f: X \rightarrow Y$ the following conditions are equivalent:

- 1) f is an n -equivalence.
- 2) For $k \leq n$, given any commutative diagram

$$\begin{array}{ccc} S^{k-1} & \xrightarrow{\varphi} & X \\ \downarrow & \nearrow \bar{\psi} & \downarrow f \\ D^k & \xrightarrow{\psi} & Y \end{array}$$

there exists a map $\bar{\psi}: D^k \rightarrow Y$ such that $\bar{\psi}|_{S^{k-1}} = \varphi$ and $f\bar{\psi} \simeq \psi \text{ (rel } S^{k-1})$.

- 3) For $k \leq n$, given any diagram

$$\begin{array}{ccc} S^{k-1} & \xrightarrow{\varphi} & X \\ \downarrow & \nearrow \bar{\psi} & \downarrow f \\ D^k & \xrightarrow{\psi} & Y \end{array}$$

and a homotopy $\Phi: f\varphi \simeq \psi|_{S^{k-1}}$ there exists a map $\bar{\psi}: D^k \rightarrow Y$ and a homotopy $\bar{\Phi}: f\bar{\psi} \simeq \psi$ such that $\bar{\psi}|_{S^{n-1}} = \varphi$ and $\bar{\Phi}|_{S^{k-1} \times [0,1]} = \Phi$.

4) The pair (M_f, X) is n -connected.

Proof. Exercise. □

14.3 Proposition. 1) If $f, g: X \rightarrow Y$ are maps such that $f \simeq g$ and f is an n -equivalence then so is g .

2) If $f: X \rightarrow Y$, $g: Y \rightarrow Z$, and any two of the maps f , g , gf are weak equivalences, then so is the third map.

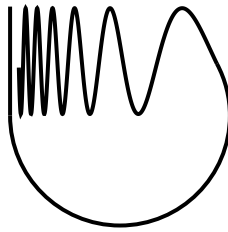
3) Every homotopy equivalence is a weak equivalence.

Proof. Exercise. □

One of the main goals of this chapter will be the proof of the following fact:

14.4 Theorem. If X, Y are CW complexes then any weak equivalence $f: X \rightarrow Y$ is a homotopy equivalence.

14.5 Note. Theorem 14.4 does not hold in general for spaces that are not CW complexes. For example, let W be the Warsaw circle (shown below). Since $\pi_i(W) = 0$ for all i , the constant map $W \rightarrow *$ is a weak equivalence. However, it is not a homotopy equivalence.



The proof Theorem 14.4 will use the following fact:

14.6 Proposition. Assume that we have a diagram

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

where (X, A) is a relative CW complex such that $\dim(X \setminus A) \leq n$ for some $n \leq \infty$, and $f: Y \rightarrow Z$ is an n -equivalence. Assume also that $\Phi: A \times [0, 1] \rightarrow Z$ is a homotopy such that $\Phi|_A \simeq gf$. Then there exists a map $\bar{h}: X \rightarrow Y$ and a homotopy $\bar{\Phi}: X \times [0, 1] \rightarrow Z$ such that $\bar{h}|_A = g$, $\bar{\Phi}: h \simeq f\bar{h}$ and $\bar{\Phi}|_{A \times [0, 1]} = \Phi$.

Proof. By induction on skeleta of (X, A) , using Proposition 14.2. □

As a special case of Proposition 14.6 we obtain:

14.7 Corollary. Assume that we have a commutative diagram

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

where (X, A) be a relative CW complex such that $\dim(X \setminus A) \leq n$ for some $n \leq \infty$, and $f: Y \rightarrow Z$ is an n -equivalence. Then there exists a map $\bar{h}: X \rightarrow Y$ such that $\bar{h}|_A = g$ and $f\bar{h} \simeq h$ (rel A).

Recall that by $[X, Y]$ we denote the set of homotopy classes of maps $X \rightarrow Y$. A map $f: Y \rightarrow Z$ induces a map of sets $f_*: [X, Y] \rightarrow [X, Z]$ given by $f_*[\varphi] = [f\varphi]$.

14.8 Corollary. Let $f: Y \rightarrow Z$ be an n -equivalence for some $n \leq \infty$. For any CW complex X the map

$$f_*: [X, Y] \rightarrow [X, Z]$$

is a bijection if $\dim X \leq n - 1$ and it is onto if $\dim X \leq n$.

Proof. The onto part follows from Corollary 14.7 with $A = \emptyset$. It remains to show that f_* is 1-1 if $\dim X \leq n - 1$. Assume then that for some $\varphi_0, \varphi_1: X \rightarrow Y$ there is a homotopy $h: X \times [0, 1] \rightarrow Z$ such that $h_0 = f\varphi_0$ and $h_1 = f\varphi_1$. This gives a commutative diagram

$$\begin{array}{ccc} X \times \{0, 1\} & \xrightarrow{\varphi_0 \sqcup \varphi_1} & Y \\ \downarrow i & \nearrow \bar{h} & \downarrow f \\ X \times [0, 1] & \xrightarrow{h} & Z \end{array}$$

Consider the relative CW complex $(X \times [0, 1], X \times \{0, 1\})$. Since $\dim X \times [0, 1] \leq n$, using Corollary 14.7 again we obtain that there exists $\bar{h}: X \times [0, 1] \rightarrow Y$ which is homotopy between φ_0 and φ_1 . □

Proof of Theorem 14.4. Let $f: X \rightarrow Y$ be a weak equivalence of CW complexes. By Corollary 14.8, the map

$$f_*: [Y, X] \rightarrow [Y, Y]$$

is a bijection. Therefore, there exists $g: Y \rightarrow X$ such that $f_*[g] = [\text{id}_Y]$. Equivalently, $fg \simeq \text{id}_Y$. Next, consider the bijection

$$f_*: [X, X] \rightarrow [X, Y]$$

We have $f_*[gf] = [fgf] = [f] = f_*[\text{id}_X]$, which gives $[gf] = [\text{id}_X]$, or equivalently $gf \simeq \text{id}_X$. Therefore f is a homotopy equivalence with a homotopy inverse g . \square

We have seen before (5.12) that two CW complexes X, Y that have isomorphic homotopy groups need not be homotopy equivalent. The issue is, that even if $\pi_i(X) \cong \pi_i(Y)$ for all $i \geq 0$, there may be no map $X \rightarrow Y$ which induces such isomorphisms. However, in two cases homotopy groups alone are enough to determine the homotopy type of a CW complex: for contractible spaces and for Eilenberg-MacLane spaces.

14.9 Proposition. *If X is a CW complex such that $\pi_i(X) = 0$ for all $i \geq 0$ then $X \simeq *$.*

Proof. The constant map $X \rightarrow *$ is weak equivalence, so by Theorem 14.4 it is a homotopy equivalence. \square

14.10 Proposition. *Let X_1, X_2 be Eilenberg-MacLane spaces of type $K(G, n)$. That is, X_1, X_2 are path connected CW complexes such that*

$$\pi_i(X_k) \cong \begin{cases} G & \text{if } i = n \\ 0 & \text{otherwise} \end{cases}$$

for $k = 1, 2$. Then $X_1 \simeq X_2$.

Proof. Recall (12.14) that we can construct an Eilenberg-MacLane space X_0 of the type $K(G, n)$ such that $X_0^{(n-1)} = *$. It will be enough to show that for any other Eilenberg-MacLane space Y of the same type there exists a weak equivalence $X_0 \rightarrow Y$. Indeed, by Theorem 14.4 this will give $X_0 \simeq Y$, and applying it to the spaces X_1 and X_2 we will obtain $X_1 \simeq X_0 \simeq X_2$.

Let then X_0, Y be Eilenberg-MacLane spaces of type $K(G, n)$ such that $X_0^{(n-1)} = *$. We can assume that the 0-cell $*$ in X_0 is the basepoint of X_0 , and let $y_0 \in Y$ be a basepoint in Y . Let $\varphi: \pi_n(X_0, *) \rightarrow \pi_n(Y, y_0)$ be an isomorphism of groups. We will construct a map $f: (X_0, *) \rightarrow (Y, y_0)$ such that $f_* = \varphi$. To do this, notice that $X_0^{(n)} = \bigvee_{i \in I} S^n$. For $k \in I$ let $j_k: S^n \hookrightarrow X_0^{(n)}$ be the inclusion of the k -th copy of S^n . Let $[ij_k] \in \pi_n(X_0, *)$ be the element represented by $S^n \xrightarrow{j_k} X_0^{(n)} \xrightarrow{i} X_0$, and let $\omega_k: S^n \rightarrow Y$ be a map such that $[\omega_k] = \varphi([ij_k])$. Define $f_n: X_0^{(n)} \rightarrow Y$ by $f_n = \bigvee_{k \in I} \omega_k$.

Assume that we can extend f_n to some map $f: X_0 \rightarrow Y$. Then f induces a homomorphism $f_*: \pi_n(X_0, *) \rightarrow \pi_n(Y, y_0)$ such that

$$f_*([ij_k]) = [\omega_k] = \varphi([ij_k]) \quad (*)$$

for all $k \in I$. By Corollary 12.6 the elements $[j_k]$ generate the group $\pi_n(X_0^{(n)}, *)$, and by Proposition 5.2 the homomorphism $i_*: \pi_n(X_0^{(n)}, *) \rightarrow \pi_n(X_0, *)$ is onto. Therefore elements $[ij_k]$ generate $\pi_n(X_0, *)$. As a consequence, the equation $(*)$ implies that $f_*([\tau]) = \varphi([\tau])$ for all $[\tau] \in \pi_n(X_0, *)$. It follows that $f_*: \pi_i(X_0, *) \rightarrow \pi_i(Y, y_0)$ is an isomorphism for $i = n$ and since all other homotopy groups of X_0 and Y are trivial, f_* is an isomorphism for all $i \neq n$ as well. Therefore f is a weak equivalence.

An extension of $f_0: X_0^{(n)} \rightarrow Y$ to $f: X_0 \rightarrow Y$ can be constructed by induction with respect to skeleta of X_0 . Assume that for some $m \geq n$ we have a map $f_m: X_0^{(m)} \rightarrow Y$ that extends f_n . Then $X_0^{(m+1)} = X_0^{(m)} \cup \bigcup_{j \in J} e_j^{m+1}$ for some $(m+1)$ -cells e_j . Let $\varphi_j: S^m \rightarrow X^{(m)}$ be the attaching map of e_j^{m+1} , and let $\bar{\varphi}_j: D^{m+1} \rightarrow X^{(m)}$ be the characteristic map. Since $\pi_m(Y) = 0$, the map $f_m \varphi_j$ extends to $\psi_j: D^{m+1} \rightarrow Y$. We define $f_{m+1}: X_0^{(m+1)} \rightarrow Y$ by

$$f_{m+1}(x) = \begin{cases} f_m(x) & \text{if } x \in X^{(m)} \\ \psi_j(\bar{\varphi}_j^{-1}(x)) & \text{if } x \in e_j \end{cases}$$

□

Using similar arguments as in the proof of Proposition 14.10 we can obtain:

14.11 Proposition. *Let $K(G, n)$, $K(H, n)$ be Eilenberg-MacLane spaces for some groups G , H and $n \geq 1$. For any homomorphism of groups $\varphi: \pi_n(K(G, n), x_0) \rightarrow \pi_n(K(H, n), y_0)$ there exists a map $f: (K(G, n), x_0) \rightarrow (K(H, n), y_0)$ such that $f_* = \varphi$.*

Proof. Exercise. □