13 | Homotopy Extension Property

In this chapter we begin work toward computing fundamental groups of CW complexes. Since a 0-dimensional CW complex is a discrete space, the fundamental group of any such complex is trivial. The first non-trivial case we will develop a formula for the fundamental group of a CW complex of dimension 1. Our main tool will be the homotopy extension property, which is one of the most important notions of algebraic topology.

13.1 Definition. Let X be a topological space, and let $A \subseteq X$. The pair (X, A) has the *homotopy extension property* if any map

$$h \colon X \times \{0\} \cup A \times [0,1] \to Y$$

can be extended to a map $\bar{h} \colon X \times [0,1] \to Y$.

The following proposition is often useful when we want to verify that the homotopy extension property holds for a given pair of (X, A):

13.2 Proposition. *A pair (X, A) has the homotopy extension property if and only if $X \times \{0\} \cup A \times [0,1]$ is a retract of $X \times [0,1]$.*

Proof. Exercise. □

The next fact implies that the homotopy extension property does not hold for arbitrary pairs of spaces:

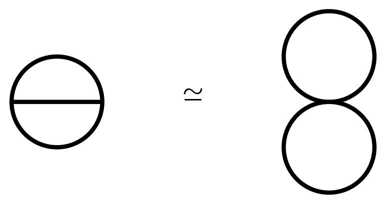
13.3 Proposition. *If a pair (X, A) has the homotopy extension property and X is a Hausdorff space then A is closed in X.*

Proof. Exercise. □

13.4 Proposition. *If a pair (X, A) has the homotopy extension property and the space A is contractible and closed in X then the quotient map $q\colon X \to X/A$ is a homotopy equivalence.*

Proof. Exercise □

13.5 Example. In Example 8.18 we have shown that the space X consisting of a circle and its diagonal is homotopy equivalent to a wedge of two circles:



We can obtain the same result as follows. Let $A \subseteq X$ be the diagonal of the circle (together with its enpoints). It will follow from Theorem 13.7 that the pair (X, A) has the homotopy extension property. Since the space A is contractible, using Proposition 13.4 we get a homotopy equivalence $X \simeq X/A$. It remains to notice that X/A is homeomorphic to $S^1 \vee S^1$.

13.6 Example. Here is an example which shows that Proposition 13.4 is not true in general, if (X, A) does not have the homotopy extension property. The *Warsaw circle* is a subspace W of $\mathbb{R}^2$ consisting of three subsets:

$$W = A \cup B \cup C$$

where:

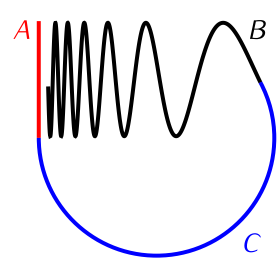
- A is a segment of the y-axis:

$$A = \{(0, y) \in \mathbb{R}^2 \mid -1 \leq y \leq 1\}$$

- B is a part of the graph of the function $f(x) = \sin\left(\frac{1}{x}\right)$:

$$B = \{(x, \sin\left(\tfrac{1}{x}\right)) \in \mathbb{R}^2 \mid 0 < x \leq \tfrac{1}{2\pi}\}$$

- C is an arc joining points $(0, -1) \in A$ and $(\frac{1}{2\pi}, 0) \in B$, and disjoint from $A \cup B$ at all other points.



Consider the pair (W, A). One can show that the quotient space W/A is homeomorphic to the circle S^1 (exercise), so in particular $\pi_1(W/A) \cong \mathbb{Z}$. On the other hand, $\pi_1(W) \cong \{1\}$ (exercise). Therefore W/A is not homotopy equivalent to W.

13.7 Theorem. *Any relative CW complex (X, Y) has the homotopy extension property.*

The proof of this theorem will use a couple of lemmas.

13.8 Lemma. *For any $n > 0$ the pair (D^n, S^{n-1}) has the homotopy extension property.*

While it is not difficult to prove Lemma 13.8 directly, we will show that it follows from a more general fact. Recall (8.15) that for a map $f: X \to Y$ the mapping cylinder of f is the space $M_f = (X \times [0,1] \sqcup Y)/\sim$ where $(x, 1) \sim f(x)$ for all $x \in X$. Notice that the space X is homeomorphic with the subspace $X \times \{0\} \subseteq M_f$.

13.9 Proposition. *For any continuous function $f: X \to Y$ the pair $(M_f, X \times \{0\})$ has the homotopy extension property.*

Proof. Exercise. □

Proof of Lemma 13.8. Let $c: S^{n-1} \to \{*\}$ be the constant function. We have a homeomorphism $f: M_c \to D^n$ given by $f(x, t) = (1-t)x$. Moreover, $f(S^{n-1} \times \{0\}) = S^{n-1} \subseteq D^n$. Since by Proposition 13.9 the pair $(M_c, S^{n-1} \times \{0\})$ has the homotopy extension property it follows that (D^n, S^{n-1}) also has this property. □

13.10 Lemma. *Let Y be any space an let $X = Y \cup \{e^n_\alpha\}_{\alpha \in I}$ be a space obtained from by attaching some number of n-cells to X. Then the pair (X, Y) has the homotopy extension property.*

Proof. To simplify notation we will assume that X is obtained from Y by attaching a single n-cell: $X = Y \cup e^n$. The proof in the general case is essentially the same. By Proposition 13.2 it will suffice to show that $X \times \{0\} \cup Y \times [0,1]$ is a retract of $X \times [0,1]$. Let $f: S^{n-1} \to Y$ be the attaching map of the cell e^n. We have a homeomorphisms

$$X \times [0,1] \simeq (D^n \times [0,1] \sqcup Y \times [0,1])/\sim$$

and

$$X \times \{0\} \cup Y \times [0,1] \simeq ((D^n \times \{0\} \cup S^{n-1} \times [0,1]) \sqcup Y \times [0,1])/\sim$$

where $(x, t) \sim (f(x), t)$ for $x \in S^{n-1}$. By Lemma 13.8 there is a retraction

$$r: D^n \times [0,1] \to D^n \times \{0\} \cup S^{n-1} \times [0,1]$$

The map

$$r \sqcup \mathrm{id}_{Y\times[0,1]} \colon ((D^n \times \{0\} \cup S^{n-1} \times [0,1]) \sqcup Y \times [0,1])/\!\sim \;\to\; (D^n \times [0,1] \sqcup Y \times [0,1])/\!\sim$$

gives the desired retraction $X \times [0,1] \to X \times \{0\} \cup Y \times [0,1]$. □

Proof of Theorem 13.7. Recall (12.7) that if (X, Y) is a relative CW complex then $X = \bigcup_{n=-1}^{\infty} X^{(n)}$ where $X^{(-1)} = Y$ and for $n \geq 0$ the subspace of $X^{(n)} \subseteq X$ obtained by attaching n-cells to $X^{(n-1)}$. By Lemma 13.10 for each $n \geq 0$ there exists a retraction

$$r_n \colon X^{(n)} \times [0,1] \to X^{(n)} \times \{0\} \cup X^{(n-1)} \times [0,1]$$

We can extend r_n to a map

$$\bar{r}_n \colon X \times \{0\} \cup X^{(n)} \times [0,1] \to X \times \{0\} \cup X^{(n-1)} \times [0,1]$$

by setting $\bar{r}_n(x,0) = (x,0)$ for $x \in X$. Define:

$$r \colon X \times [0,1] \to X \times \{0\} \cup Y \times [0,1]$$

by $r(x,t) = \bar{r}_0 \circ \bar{r}_1 \circ \ldots \circ \bar{r}_n(x,t)$ if $x \in X^{(n)}$, $n \geq 0$, and $r(x,t) = (x,t)$ if $x \in X^{(-1)} = Y$. One can check that r is a well defined, continuous retraction (exercise).

□

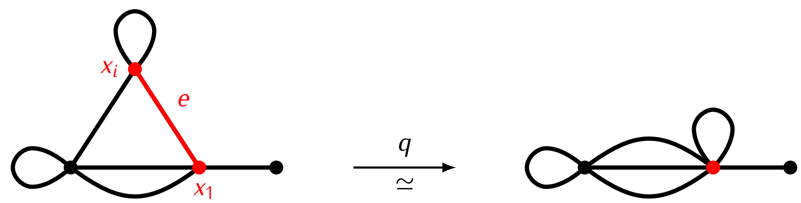
13.11 Theorem. *If X is a path connected finite CW complex of dimension 1 then $X \simeq \bigvee_{i=1}^{n} S^1$ where*

$$n = \begin{pmatrix} \textit{number of} \\ \textit{1-cells of } X \end{pmatrix} - \begin{pmatrix} \textit{number of} \\ \textit{0-cells of } X \end{pmatrix} + 1$$

13.12 Corollary. *If X is a path connected finite CW complex of dimension 1 then $\pi_1(X) \cong *_{i=1}^{n}\mathbb{Z}$ where n is defined as in Theorem 13.11.*

Proof. This follows from Theorem 13.11 and Example 10.19. □

Proof of Theorem 13.11. We will argue by induction with respect to the number k of 0-cells in X. If $k = 1$ then the statement is obvious. Assume then that the statement of theorem is true for all complexes whose number of 0-cells is k, and let X be a path connected finite 1-dimensional CW complex whose set of 0-cells is $\{x_1, x_2, \ldots, x_{k+1}\}$ for some $k \geq 1$. Since X is path connected there exists a 1-cell e in X that joins x_1 with some other 0-cell x_i. Let A denote the subcomplex of X consisting of the cells x_1, x_i and e. Notice that A is homeomorphic to the closed interval $[0,1]$. The pair (X, A) is a relative CW complex, so by Theorem 13.7 it satisfies the homotopy extension property. Since A is contractible, by Proposition 13.4 the quotient map $q \colon X \to X/A$ is a homotopy equivalence.



The space X/A has the structure of a 1-dimensional CW complex with one 0-cell and one 1-cell less than X. Therefore, by the inductive assumption the statement of the theorem holds for X/A, and so it also holds for X.

□

Theorem 13.11 can be generalized to infinite 1-dimensional complexes:

13.13 Theorem. *If X is a path connected 1-dimensional CW complex then $X \simeq \bigvee_{I \in I} S^1$ for some set I. As a consequence $\pi_1(X) \cong *_{i \in I} \mathbb{Z}$.*

13.14 Note. For a finite CW complex X, let $c_n(X)$ denote the number of n-cells of X. Theorem 13.11 implies that if X is a path connected CW complex of dimension 1, then the number $c_1(X) - c_0(X)$ depends only on the homotopy type of X: if Y is another such CW complex and $X \simeq Y$ then $c_1(X) - c_0(X) = c_1(Y) - c_0(Y)$. This observation can be generalized as follows. The *Euler characteristic* of a finite CW complex X is the integer $\chi(X) = \sum_n (-1)^n c_n(X)$. One can show that if X and Y are finite CW complexes and $X \simeq Y$ then $\chi(X) = \chi(Y)$.

Exercises to Chapter 13

E13.1 Exercise. Prove Proposition 13.2.

E13.2 Exercise. Prove Proposition 13.4.

E13.3 Exercise. Show that if a pair (X, A) has the homotopy extension property then for any space Y the pair $(X \times Y, A \times Y)$ also has the homotopy extension property.

E13.4 Exercise. Prove Proposition 13.9.

E13.5 Exercise. Given spaces X, Y let $[X, Y]$ denote the set of homotopy classes of maps $f \colon X \to Y$. A map of spaces $g \colon X \to X'$ induces a map of sets $g^* \colon [X', Y] \to [X, Y]$ given by $g^*([f]) = [fg]$. Let $A \subseteq X$, let $j \colon A \to X$ be the inclusion and $q \colon X \to X/A$ be the quotient map. For any Y this induces maps of sets

$$[X/A, Y] \xrightarrow{q^*} [X, Y] \xrightarrow{j^*} [A, Y]$$

Show that if the pair (X, A) has the homotopy extension property then $j^*[f]$ is the homotopy class of a constant map $A \to Y$ if and only if $[f] = q^*[f']$ for some $f' \colon X/A \to Y$.

E13.6 Exercise. Let (X, x_0), (Y, y_0) be pointed spaces. Denote by $[X, Y]_*$ the set of pointed homotopy classes of basepoint preserving maps $X \to Y$. That is, any map $f \colon (X, x_0) \to (Y, y_0)$ defines an element $[f]_* \in [X, Y]_*$, and $[f]_* = [g]_*$ if $f \simeq g$ (rel $\{x_0\}$). Also, let $[X, Y]$ be the set of homotopy classes of all functions $X \to Y$. Thus, any map $f \colon X \to Y$ defines an element $[f] \in [X, Y]$, and $[f] = [g]$ if $f \simeq g$ (there is no assumption that maps or homotopies preserve the basepoints). Let

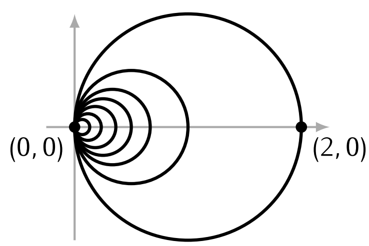
$$\Phi \colon [X, Y]_* \to [X, Y]$$

be a function given by $\Phi([f]_*) = [f]$.

a) Assume that the pair (X, x_0) has the homotopy extension property, and Y is a path connected space. Show that Φ is onto.

b) Assume that in addition the group $\pi_1(Y, y_0)$ is trivial. Show that Φ is a bijection.

E13.7 Exercise. The *Hawaiian earring* space is a subspace $X \subseteq \mathbb{R}^2$ given by $X = \bigcup_{n=1}^{\infty} C_n$ where C_n is the circle with radius $\frac{1}{n}$ and center at the point $(\frac{1}{n}, 0)$:



Denote $x_0 = (0, 0)$ and $y_0 = (2, 0)$. Let $\mathrm{id}_X \colon X \to X$ be the identity map.

a) Show that there does not exist a map $g \colon X \to X$ such that $\mathrm{id}_X \simeq g$ and $g(x_0) = y_0$.

b) Show that the pair (X, x_0) does not have the homotopy extension property. (Hint: use Exercise 13.6).

E13.8 Exercise. Let (X, Y) be a relative CW complex, let $j \colon Y \to X$ be the inclusion map, and let C_j be the mapping cone of j. Show that C_j is homotopy equivalent to the space X/Y.

E13.9 Exercise. Assume that (X, A) is a pair with the homotopy extension property such that the inclusion map $i \colon A \hookrightarrow X$ is a homotopy equivalence.

a) Show that A is a retract of X.

b) Show that A is a strong deformation retract of X.

E13.10 Exercise. Let $f\colon (X, x_0) \to (Y, y_0)$ be a map of pointed spaces. Show that if X is a path connected 1-dimensional CW complex and $f_*\colon \pi_1(X, x_0) \to \pi_1(Y, y_0)$ is the trivial homomorphism then f is homotopic to a constant map.

E13.11 Exercise. Let X be a finite, path connected CW complex.

a) Show that X is homotopy equivalent to a CW complex X' which has only one 0-cell.

b) Show that if $\pi_1(X) = \{1\}$ then X is homotopy equivalent to a CW complex X'' which has only one 0-cell and no 1-cells.