

MATH 611 PROBLEM SET 1 (DUE 9/4)

HIDENORI SHINOHARA

Exercise 0.1. (Exercise 4, Chapter 0) A deformation retraction in the weak sense of a space X to a subspace A is a homotopy $f_t : X \rightarrow X$ such that $f_0 = \text{Id}$, $f_1(X) \subset A$, and $f_t(A) \subset A$ for all t . Show that if X deformation retracts to A in this weak sense, then the inclusion $A \rightarrow X$ is a homotopy equivalence.

Proof. Let $i : A \rightarrow X$ denote the inclusion. Let $F : X \times I \rightarrow X$ denote the associated map $(x, t) \rightarrow f_t(x)$. Then F is a continuous function by the definition of a homotopy.

Let $f : X \rightarrow A$ be defined by $f(x) = F(x, 1) = f_1(x)$. This definition makes sense because $f_1(X) \subset A$. We claim that $f_1 \circ i \simeq \text{Id}_A$ and $i \circ f_1 \simeq \text{Id}_X$.

Consider $G : A \times I \rightarrow A$ such that $G(a, t) = F(a, t)$ for all $(a, t) \in A \times I$. This definition makes sense because $f_t(A) \subset A$ for all t .

Then G is a homotopy in A between $f \circ i$ and Id_A because:

- G is a restriction of F , so G is continuous.
- $\forall a \in A, G(a, 0) = F(a, 0) = f_0(a) = \text{Id}_X(a) = \text{Id}_A(a)$.
- $\forall a \in A, G(a, 1) = F(a, 1) = f(a) = f(i(a)) = (f \circ i)(a)$.

Therefore, $f \circ i \simeq \text{Id}_A$.

F is a homotopy between f_0 and f_1 .

- We are given that $f_0 = \text{Id}_X$.
- For any $x \in X$, $(i \circ f)(x) = i(f(x)) = f(x) = f_1(x)$, so $i \circ f = f_1$.

Therefore, F is a homotopy between Id_X and $i \circ F$, so $i \circ f \simeq \text{Id}_X$.

In conclusion, i is indeed a homotopy equivalence. \square

Exercise 0.2. (Exercise 5, Chapter 0) Show that if a space X deformation retracts to a point $x \in X$, then for each neighborhood U of x in X there exists a neighborhood $V \subset U$ of x such that the inclusion map $V \rightarrow U$ is nullhomotopic.

Proof. Let $p \in X$ be a point to which X deformation retracts. Since X deformation retracts to p , there exists a map $F : X \times I \rightarrow X$ such that

- (1) $\forall x \in X, F(x, 0) = x$.
- (2) $\forall x \in X, F(x, 1) = p$.

- (3) $\forall t \in I, F(p, t) = p$.
- (4) F is continuous.

Let U be a neighborhood of p . Then $F^{-1}(U)$ is an open subset of the product space $X \times I$. By the 3rd property of F mentioned above, the slice $\{p\} \times I$ is a subset of $F^{-1}(U)$. Since I is compact, there must be a open subset V of X such that $\{p\} \times I \subset V \times I \subset F^{-1}(U)$ by the tube lemma.

We claim that this V is a desired subset.

- V is an open subset of X .
- Since $\{p\} \times I \subset V \times I$, $p \in V$.
- Since $V \times I \subset F^{-1}(U)$, $F(V \times I) \subset U$. This implies that $\forall v \in V$, $F(v, 0) = v \in U$. Therefore, $V \subset U$.
- We claim that the inclusion map $i : V \rightarrow U$ is nullhomotopic. Let $e_p : V \rightarrow U$ denote the constant map at p , $G : V \times I \rightarrow U$ be defined by $G(x, t) = F(x, t)$ for all $x \in V, t \in I$.
 - G indeed maps $V \times I$ into U because $F(V \times I) \subset U$. Therefore, G is well-defined.
 - Since G is the restriction of F to $V \times I$ and F is continuous, G is continuous.
 - $\forall x \in V, G(x, 0) = F(x, 0) = x = i(x)$.
 - $\forall x \in V, G(x, 1) = F(x, 1) = p = e_p(x)$.

Thus i is indeed nullhomotopic.

□

Exercise 0.3. (Exercise 9, Chapter 0) Show that a retract of a contractible space is contractible.

Proof. Let X be a contractible space. Then Id_X is homotopic to a constant map. This implies the existence of a fixed point $p \in X$ and a continuous function $F : X \times I \rightarrow X$ such that

- $\forall x \in X, F(x, 0) = x$,
- $\forall x \in X, F(x, 1) = p$.

Let $A \subset X$ be a retract of X , and let $r : X \rightarrow A$ denote a retraction. In other words, $r(X) = A$ and $r|_A = \text{Id}_A$.

Let $G : A \times I \rightarrow A$ be the restriction of $r \circ F$ to $A \times I$. This makes sense because F maps $A \times I$ into X , and r maps X into A . We claim that G is a homotopy between Id_A and the constant map $e_{r(p)}$ such that $e_{r(p)}(a) = r(p)$ for all $a \in A$.

- $r \circ F$ is continuous since it is a composition of continuous functions. G is a restriction of a continuous function, so G is continuous.
- $G(a, 0) = r(F(a, 0)) = r(a) = a = \text{Id}_A(a)$.

- $G(a, 1) = r(F(a, 1)) = r(p) = e_{r(p)}(a)$.

Therefore, G is indeed a homotopy between Id_A and the constant map at $r(p)$. Since the identity map is homotopic to a constant map, A is contractible. \square

Exercise 0.4. (Exercise 13, Chapter 0) Show that any two deformation retractions r_t^0 and r_t^1 of a space X onto a subspace A can be joined by a continuous family of deformation retractions r_t^s , $0 \leq s \leq 1$, of X onto A , where continuity means that the map $X \times I \times I \rightarrow X$ sending (x, s, t) to $r_t^s(x)$ is continuous.

Proof. Let $F : X \times I \times I \rightarrow X$ be defined such that

$$F(x, t, s) = \begin{cases} r_{t(1-2s)}^0(x) & (s \in [0, 1/2]) \\ r_{t(2s-1)}^1(x) & (s \in [1/2, 1]) \end{cases}.$$

We claim that F is well-defined and satisfies the desired properties.

- Let $s = 1/2$. $r_{t(1-2s)}^0(x) = r_0^0(x) = x$ because r_t^0 is a deformation retraction. Similarly, $r_{t(2s-1)}^1(x) = r_0^1(x) = x$ because r_t^1 is a deformation retraction. Therefore, F is well defined when $s = 1/2$. Moreover, by the pasting lemma, F is continuous. This is because the intersection $X \times I \times [0, 1/2] \cap X \times I \times [1/2, 1] = X \times I \times \{1/2\}$ is closed.
- $F(x, t, 0) = r_t^0(x)$ for any $x \times t \in X \times I$.
- $F(x, t, 1) = r_t^1(x)$ for any $x \times t \in X \times I$.

Therefore, F maps $X \times I \times I \rightarrow X$ continuously sending (x, s, t) to $r_t^s(x)$. \square

Exercise 0.5. (Exercise 20, Chapter 1.1) Suppose $f_t : X \rightarrow X$ is a homotopy such that f_0 and f_1 are each the identity map. Use Lemma 1.19 to show that for any $x_0 \in X$, the loop $f_t(x_0)$ represents an element of the center of $\pi_1(X, x_0)$.

Proof. Let $x_0 \in X$ be given. Let $f : I \rightarrow X$ be the loop defined such that $f(t) = f_t(x_0)$.

- $f_t : X \rightarrow X$ is a homotopy.
- f is a path formed by the images of the base point x_0 .

By Lemma 1.19, the following diagram commutes.

$$\begin{array}{ccc}
 & \pi_1(X, f_1(x_0)) & \\
 & \uparrow (f_1)_* & \\
 \pi_1(X, x_0) & & \\
 & \downarrow (f_0)_* & \\
 & \pi_1(X, f_0(x_0)) & \\
 & \downarrow \beta_f &
 \end{array}$$

$(f_0)_* = (f_1)_* = (\text{Id}_X)_* = \text{Id}_{\pi_1(X, x_0)}$ by a basic property of induced homomorphisms (P.34 of Hatcher). Since $f_0 = f_1 = \text{Id}_X$, $f_0(x_0) = f_1(x_0) = x_0$. Therefore, the diagram above can be simplified as following:

$$\begin{array}{ccc}
 & \pi_1(X, x_0) & \\
 & \uparrow \text{Id} & \\
 \pi_1(X, x_0) & & \\
 & \downarrow \text{Id} & \\
 & \pi_1(X, x_0) & \\
 & \downarrow \beta_f &
 \end{array}$$

Let $[g] \in \pi_1(X, x_0)$. Then by the diagram above, we have $\text{Id}([g]) = \text{Id}(\beta_f([g]))$. This implies $[g] = [f \cdot g \cdot \bar{f}]$. Therefore, $[g] \cdot [f] = [f] \cdot [g]$, so $[f]$ commutes with every element in $\pi_1(X, x_0)$. Hence, $[f] \in Z(\pi_1(X, x_0))$. \square