

Algebraic Topology Problem Set 6 — Solutions

Q1: First note that $g_* f_* = (gf)_* = 1_{X_*} = 1_{\pi_0 X}$, so $g_* f_*(u) = u$ for all elements $u \in \pi_0 X$.

- (a) Suppose that $f_*(u) = f_*(v)$. Then $g_* f_*(u) = g_* f_*(v)$, or in other words $u = v$. This shows that f_* is injective.
- (b) Suppose that $u \in \pi_0 X$. If we put $v = f_*(u) \in \pi_0 Y$, we find that $g_*(v) = g_* f_*(u) = u$. As $u = g_*(v)$ we see that u is in the image of g . This holds for all u , so g_* is surjective.
- (c) Suppose that $A = \{a_1, \dots, a_n\}$. (We assume that this lists all the elements without repetition, so $a_i \neq a_j$ when $i \neq j$, and $|A| = n$.) Suppose that $j: A \rightarrow B$ is injective. Then $j(a_1), \dots, j(a_n)$ are all elements of B , and they are all different because j is injective. Thus B has at least n different elements, i.e. $|B| \geq n$. Suppose instead that $q: B \rightarrow A$ is surjective. Each element a_i must lie in the image of q , so $a_i = q(b_i)$ for some $b_i \in B$. If $b_i = b_j$ then we must have $q(b_i) = q(b_j)$, or in other words $a_i = a_j$, but this only happens when $i = j$. This shows that b_1, \dots, b_n are distinct elements of B , so again $|B| \geq n$.

Q2:

- (a) Put $u(t) = h(t, x)$ and $v(t) = h(t, y)$, so u is a path from x to a , and v is a path from y to a . Then put $w = u * v$, or equivalently

$$w(t) = \begin{cases} h(2t, x) & \text{if } 0 \leq t \leq 1/2 \\ h(2 - 2t, y) & \text{if } 1/2 \leq t \leq 1 \end{cases}$$

This gives a path from x to g .

- (b) First put $b = f(a)$ and $h'(t, y) = f(h(t, g(y)))$. Then $h'(0, y) = f(h(0, g(y))) = f(g(y))$ and $h'(1, y) = f(h(1, g(y))) = f(a) = b$ for all y . In other words, h' is a homotopy between $f g$ and the constant map c_b with value b . We are also given a homotopy k from 1_Y to $f g$, and we can combine these to get a homotopy $m: I \times Y \rightarrow Y$ between 1_Y and c_b . Explicitly, the formula is

$$m(t, y) = \begin{cases} k(2t, y) & \text{if } 0 \leq t \leq 1/2 \\ h'(2t - 1, y) & \text{if } 1/2 \leq t \leq 1. \end{cases}$$

Q3:

- (a) Suppose that $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$. Then

$$\begin{aligned} AM &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} b & a \\ d & c \end{pmatrix} \\ MA &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} c & d \\ a & b \end{pmatrix} \end{aligned}$$

Thus $AM = MA$ if and only if $c = b$ and $d = a$, so A has the form $\begin{pmatrix} a & b \\ b & a \end{pmatrix}$. If so then $\det(A) = a^2 - b^2 = (a + b)(a - b)$.

- (b) Put $X = \{A \in GL_2\mathbb{C} \mid AM = MA\}$. If $A \in X$ then A must have the form $\begin{pmatrix} a & b \\ b & a \end{pmatrix}$ with $(a + b)(a - b) = \det(A) \neq 0$, so $a + b$ and $a - b$ are nonzero. We can thus define a map $f: X \rightarrow \mathbb{C} \setminus \{0\} \times \mathbb{C} \setminus \{0\}$ by $f(A) = (a + b, a - b)$. Note that if $u = a + b$ and $v = a - b$ then $a = (u + v)/2$ and $b = (u - v)/2$. It follows that f is a homeomorphism, with inverse

$$f^{-1}(u, v) = \frac{1}{2} \begin{pmatrix} u + v & u - v \\ u - v & u + v \end{pmatrix}.$$

- (c) As $\mathbb{C} \setminus \{0\}$ is homotopy equivalent to S^1 , we deduce that X is homotopy equivalent to $S^1 \times S^1$, which is the torus.

Topology Problem Solutions

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