

## 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  $y$ .

- (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

**Frank Harary**



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## **Table of Contents Topology Problem Solutions**

1. Understanding the eBook Topology Problem Solutions
  - The Rise of Digital Reading Topology Problem Solutions
  - Advantages of eBooks Over Traditional Books
2. Identifying Topology Problem Solutions
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Topology Problem Solutions
  - User-Friendly Interface
4. Exploring eBook Recommendations from Topology Problem Solutions
  - Personalized Recommendations
  - Topology Problem Solutions User Reviews and Ratings
  - Topology Problem Solutions and Bestseller Lists
5. Accessing Topology Problem Solutions Free and Paid eBooks
  - Topology Problem Solutions Public Domain eBooks
  - Topology Problem Solutions eBook Subscription Services
  - Topology Problem Solutions Budget-Friendly Options

6. Navigating Topology Problem Solutions eBook Formats
  - ePub, PDF, MOBI, and More
  - Topology Problem Solutions Compatibility with Devices
  - Topology Problem Solutions Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Topology Problem Solutions
  - Highlighting and Note-Taking Topology Problem Solutions
  - Interactive Elements Topology Problem Solutions
8. Staying Engaged with Topology Problem Solutions
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Topology Problem Solutions
9. Balancing eBooks and Physical Books Topology Problem Solutions
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Topology Problem Solutions
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Topology Problem Solutions
  - Setting Reading Goals Topology Problem Solutions
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Topology Problem Solutions
  - Fact-Checking eBook Content of Topology Problem Solutions
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
  - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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