

Algebraic Topology, Examples 4

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Questions marked by * are optional.

1. Show that if $n \neq m$ then \mathbb{R}^n and \mathbb{R}^m are not homeomorphic.
2. For each of the following exact sequences of abelian groups and homomorphisms say as much as possible about the unknown group G and homomorphism α .

(i) $0 \longrightarrow \mathbb{Z}/2 \longrightarrow G \longrightarrow \mathbb{Z} \longrightarrow 0,$

(ii) $0 \longrightarrow \mathbb{Z}/2 \longrightarrow G \longrightarrow \mathbb{Z}/2 \longrightarrow 0,$

(iii) $0 \longrightarrow G \longrightarrow \mathbb{Z} \xrightarrow{\alpha} \mathbb{Z} \longrightarrow \mathbb{Z}/2 \longrightarrow 0,$

(iv) $0 \longrightarrow \mathbb{Z}/3 \longrightarrow G \longrightarrow \mathbb{Z}/2 \longrightarrow \mathbb{Z} \xrightarrow{\alpha} \mathbb{Z} \longrightarrow 0.$

3. Consider a commutative diagram

$$\begin{array}{ccccccccc} A_1 & \xrightarrow{f_1} & A_2 & \xrightarrow{f_2} & A_3 & \xrightarrow{f_3} & A_4 & \xrightarrow{f_4} & A_5 \\ \downarrow h_1 & & \downarrow h_2 & & \downarrow h_3 & & \downarrow h_4 & & \downarrow h_5 \\ B_1 & \xrightarrow{g_1} & B_2 & \xrightarrow{g_2} & B_3 & \xrightarrow{g_3} & B_4 & \xrightarrow{g_4} & B_5 \end{array}$$

in which the rows are exact and each square commutes. If h_1 , h_2 , h_4 , and h_5 are isomorphisms, show that h_3 is too.

4. For triangulated surfaces X and Y , let $X \# Y$ be the surface obtained by cutting out a 2-simplex from both X and Y and then gluing together the two copies of $\partial\Delta^2$ formed.

- (i) Use the Mayer–Vietoris sequence to compute the homology of $\Sigma_g \# \Sigma_h$, and deduce that it is homeomorphic to Σ_{g+h} .
- (ii) Use the Mayer–Vietoris sequence to compute the homology of $\Sigma_g \# S_n$, and hence deduce that it is homeomorphic to S_{n+2g} .

[Recall that Σ_g denotes the orientable surface of genus g and that S_n denotes the non-orientable surface of genus n .]

5. The *rank* of a finitely generated abelian group A is the unique integer r such that $A \cong \mathbb{Z}^r \oplus A'$ for finite A' . The *Euler characteristic* of a simplicial complex K is defined to be

$$\chi(K) = \sum_{i \geq 0} (-1)^i \text{rank } H_i(K) .$$

- (a) Prove that $\chi(K) = \sum_{i \geq 0} (-1)^i \text{rank } C_i(K)$, where $C_i(K)$ are the chain groups of K .
- (b) Deduce that $\chi(K) = \sum_{i \geq 0} (-1)^i \# \{i\text{-simplices of } K\}$.

6. Let $p : \tilde{X} \rightarrow X$ be a finite-sheeted covering space, and $h : |K| \rightarrow X$ a triangulation. Show that there is an $r \geq 1$ and triangulation $g : |L| \rightarrow \tilde{X}$ so that the composition $h^{-1} \circ p \circ g : |L| \rightarrow |K^{(r)}|$ is a simplicial map. If p has n sheets, show that $\chi(\tilde{X}) = n \cdot \chi(X)$. Hence show that Σ_g is a covering space of Σ_h if and only if $\frac{1-g}{1-h}$ is an integer.

[Hint: If $g = 1 + k \cdot (h - 1)$, show that \mathbb{Z}/k acts freely and properly discontinuously on a particular orientable surface of genus g , and identify the quotient.]

7. Let A be a 2×2 matrix with entries in \mathbb{Z} . Show that the linear map $A : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ preserves the equivalence relation $(a, b) \sim (a', b') \iff (a - a', b - b') \in \mathbb{Z}^2$, and so induces a continuous map f_A from the torus T to itself. Compute the effect of the continuous map f_A on the homology of T .

8. * Let K be a simplicial complex in \mathbb{R}^m , and consider this as lying inside \mathbb{R}^{m+1} as the vectors of the form $(x_1, \dots, x_n, 0)$. Let $e_+ = (0, \dots, 0, 1) \in \mathbb{R}^{m+1}$ and $e_- = (0, \dots, 0, -1) \in \mathbb{R}^{m+1}$. The *suspension* of K is the simplicial complex in \mathbb{R}^{m+1}

$$SK := K \cup \{ \langle v_0, \dots, v_n, e_+ \rangle, \langle v_0, \dots, v_n, e_- \rangle \mid \langle v_0, \dots, v_n \rangle \in K \}.$$

- (i) Show that SK is a simplicial complex, and that if $|K| \cong S^n$ then $|SK| \cong S^{n+1}$.
- (ii) Using the Mayer–Vietoris sequence, show that if K is connected then $H_0(SK) \cong \mathbb{Z}$, $H_1(SK) = 0$, and $H_i(SK) \cong H_{i-1}(K)$ if $i \geq 2$.
- (iii) If $f : K \rightarrow K$ is a simplicial map, let $Sf : SK \rightarrow SK$ be the unique simplicial map which agrees with f on the subcomplex K and fixes the points e_+ and e_- . Show that under the isomorphism in (ii), the maps f_* and Sf_* agree. [It may help to describe the isomorphism in (ii) at the level of chains.]
- (iv) Deduce that for every $n \geq 1$ and $d \in \mathbb{Z}$ there is a map $f : S^n \rightarrow S^n$ so that f_* induces multiplication by d on $H_n(S^n) \cong \mathbb{Z}$.