

- 1** Suppose M is a compact connected 3-manifold and ω is a nowhere zero 1-form defined on M . Suppose that the distribution $\ker \omega$ is integrable, and $\ker = T\mathcal{F}$ for a foliation \mathcal{F} .

1.1 Show that $\omega \wedge d\omega = 0$

1.2 Use a partition of unity to show that there is a 1-form α such that $d\omega = \alpha \wedge \omega$.

1.3 Show $d\alpha \wedge \omega = 0$.

1.4 Suppose that α' is some other 1-form satisfying $d\omega = \alpha' \wedge \omega$. Show that $\alpha' = \alpha + g\omega$ for some function g , and that $\alpha \wedge d\alpha = \alpha' \wedge d\alpha'$.

1.5 Suppose that ω' is a nowhere zero 1-form and $\ker \omega = \ker \omega'$. If $d\omega' = \gamma \wedge \omega$, show that $\alpha \wedge d\alpha - \gamma \wedge d\gamma$ is exact.

- 2** On the compact connected manifold M , suppose α is a p -form and β is an $(n - p - 1)$ -form. Suppose ∂M has two components: $\partial_0 M$ and $\partial_1 M$. Let i_0 and i_1 be the inclusions of $\partial_0 M$ and $\partial_1 M$ into M . Given that $i_0^* \alpha = 0$ and $i_1^* \beta = 0$, show that

$$\int_M d\alpha \wedge \beta = (-1)^{p+1} \int_M \alpha \wedge d\beta$$

- 3** Suppose $f : S^1 \rightarrow \mathbb{R}^2$ and $g : S^1 \rightarrow \mathbb{R}^2$ are smooth embeddings. Let

$$M = \{(a, b, \vec{v}) \in S^1 \times S^1 \times \mathbb{R}^2 : f(a) - g(b) = \vec{v}\}.$$

Show that M is a compact submanifold of $S^1 \times S^1 \times \mathbb{R}^2$. Let $\pi : M \rightarrow \mathbb{R}^2$ be the projection $\pi(a, b, \vec{v})$. Apply Sard's Theorem to π and deduce that for almost every $\vec{v} \in \mathbb{R}^2$, $f(S^1)$ is transverse to $g(S^1) + \vec{v}$.

- 4 Suppose that $f : M \rightarrow N$ is a C^∞ map, M and N are compact connected n -manifolds, and $\text{rank}(df) = n$. Show that f is a covering map.
- 5 Let X be a polyhedron, A a subpolyhedron, $p : \tilde{X} \rightarrow X$ the universal covering space of X and \bar{A} the path component of $p^{-1}(A)$ containing the equivalence class of the constant path at $x_0 \in A$.
 - 5.1 Give an example in which $\bar{p} : \bar{A} \rightarrow A$ (where \bar{p} is the restriction of p) is not the universal covering space of A .
 - 5.2 Prove that $\bar{p} : \bar{A} \rightarrow A$ is the covering space of the kernel of $i_* : \pi_1(A, x_0) \rightarrow \pi_1(X, x_0)$ where i is inclusion.
- 6 Let D^n be the unit ball in \mathbb{R}^n , S^{n-1} its boundary, and $0 \in \mathbb{R}^n$ the origin.
 - 6.1 Prove that the inclusion $i : (D^n, S^{n-1}) \rightarrow (D^n, D^n - 0)$ induces an isomorphism $i_* : H_n(D^n, S^{n-1}) \rightarrow H_n(D^n, D^n - 0)$.
 - 6.2 Prove that i is not a homotopy equivalence of pairs, that is, there is no map $g : (D^n, D^n - 0) \rightarrow (D^n, S^{n-1})$ such that gi and ig are homotopic, as maps of pairs, to identity maps.
- 7 Given a map $f : X \rightarrow X$ of a polyhedron, there is an exact sequence

$$\rightarrow H_k(X) \xrightarrow{1-f_*} H_k(X) \rightarrow H_k(T_f) \rightarrow H_{k-1}(X) \rightarrow$$

where T_f is the mapping torus of f . Use the sequence to calculate the homology of the 3-manifold M obtained from $S^2 \times I$ by identifying $(x, 0)$ to $(-x, 1)$ for all $x \in S^2$.

- 8 Let $A \subseteq X \subseteq Q$ and consider

$$H_k(Q, A) \xrightarrow{i_*} H_k(Q, X) \xrightarrow{\partial} H_{k-1}(X, A)$$

where i is inclusion and $\partial[z] = [\partial_k[z]]$ for $\partial_k : H_k(Q, X) \rightarrow H_{k-1}(X)$ that comes from the exact sequence of (Q, X) .

- 8.1 Prove that ∂ is well-defined.
- 8.2 Prove that the image of i_* equals the kernel of ∂ .
- 9 Let $J(X, x_0) \subseteq \pi_1(X, x_0)$ be the subgroup of cyclic classes, where a class α is *cyclic* if there is a homotopy $\{h_t : X \rightarrow X\}$ with $h_0 = h_1 = \text{identity}$ such that $[h_t(x_0)] = \alpha$.
 - 9.1 Prove that $J(X, x_0)$ is contained in the center of $\pi_1(X, x_0)$.
 - 9.2 Prove that if X is a topological group, then $J(X, x_0) = \pi_1(X, x_0)$.