MATH 612(HOMEWORK 4)

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Exercise. (8) By using cellular cohomology, we obtain

$$H^i(X; \mathbb{Z}) = H^i(Y; \mathbb{Z}) = \begin{cases} \mathbb{Z} & (i = 0, 4), \\ \mathbb{Z}_p & (i = 3), \end{cases}$$

$$H^i(X; \mathbb{Z}_p) = H^i(Y; \mathbb{Z}_p) = \begin{cases} \mathbb{Z}_p & (i = 0, 2, 3, 4), \end{cases}$$

Therefore, we cannot distinguish X from Y by looking at the cohomology groups. When using the coefficient $\mathbb{Z}$, cup products are simply 0 because nontrivial cohomology groups are of order 3 and 4. Thus we cannot distinguish X from Y by looking at the cohomology rings of X and Y. Since $H^i(Y; \mathbb{Z}_p) = H^i(S^4; \mathbb{Z}_p) \oplus H^i(M(\mathbb{Z}_p, 2); \mathbb{Z}_p)$ and the cup product of elements from different "components" in a wedge sum is 0, cup products in $H^*(Y; \mathbb{Z}_p)$ are all 0. On the other hand, the cup product $\alpha \smile \alpha$ where α is a generator of $H^2(\mathbb{C}P^2; \mathbb{Z}_p)$ is nontrivial because $\alpha \smile \alpha$ is a generator of $H^4(\mathbb{C}P^2; \mathbb{Z}_p)$.

Exercise. (5) Consider the canonical map $\mathbb{Z}_{2k} \to \mathbb{Z}_2$. It induces homomorphisms $\phi : H^i(\mathbb{R}P^\infty; \mathbb{Z}_{2k}) \to H^i(\mathbb{R}P^\infty; \mathbb{Z}_2)$. By cellular cohomology, $H^0(\mathbb{R}P^\infty; \mathbb{Z}_{2k}) = \mathbb{Z}_{2k}$ and $H^i(\mathbb{R}P^\infty; \mathbb{Z}_{2k}) = \mathbb{Z}_2$ for $i \geq 1$. Let α denote a generator of $H^1(\mathbb{R}P^\infty; \mathbb{Z}_{2k})$, which equals the coset represented by k, and let β denote a generator of $H^2(\mathbb{R}P^\infty; \mathbb{Z}_{2k})$, which equals the coset represented by 1, and let γ denote a generator of $H^1(\mathbb{R}P^\infty; \mathbb{Z}_2)$. Then $2\alpha = 2\beta = 0$. Then ϕ on the even dimensions are all isomorphisms because $1 \mapsto 1$.

Suppose k is even. Then $\phi(\alpha) = 0$ because k is even. Moreover, $\phi(\alpha^2) = (\phi(\alpha))^2 = 0$. Since ϕ is an isomorphism on the even dimensions, $\alpha^2 = 0$. Thus $\alpha - k\beta = 0$.

Suppose k is odd. Then the ϕ are isomorphisms on the odd dimensions as well because $\overline{k} \mapsto 1$. Then $\phi(\beta) = \gamma^2 = \phi(\alpha)^2$, so $\alpha^2 = \beta$. Thus $\alpha - k\beta = 0$.

Therefore, we obtained the relations $2\alpha, 2\beta, \alpha^2 - k\beta$.

> Show why these are all the relations.

Exercise. (9) The quotient map $\mathbb{Z} \to \mathbb{Z}_p$ induces a map $f : H^*(X) \to H^*(X; \mathbb{Z}_p)$. Then we have a map $H^*(X) \times \mathbb{Z}_p \to H^*(X; \mathbb{Z}_p)$ defined by $(\alpha, a) \mapsto af(\alpha)$. Since this is bilinear, we obtain a map $\phi : H^*(X) \otimes \mathbb{Z}_p \to H^*(X; \mathbb{Z}_p)$. Suppose $\phi(\alpha \otimes a) = 0$. Without loss of generality, we assume $a = 1$. Then $f(\alpha)(\sigma) = 0$ for any σ. In other words, $\alpha(\sigma) \in p\mathbb{Z}$ for any σ. This implies the existence of $\beta \in H^*(X)$ such that $\alpha = p\beta$. Then $\alpha \otimes 1 = \beta \otimes 0 = 0$. Thus the kernel is 0, so ϕ is injective.

By the universal coefficient theorem, we obtain $H^k(X; \mathbb{Z}_p) \cong \operatorname{Hom}(H_k(X); \mathbb{Z}_p) \cong \coprod \mathbb{Z}_p$. Similarly, $H^k(X) \cong \coprod \mathbb{Z}$. Then ϕ is the ring homomorphism from $\coprod \mathbb{Z}$ to $\coprod \mathbb{Z}_p$ when restricted to each dimension, so it is surjective.

Exercise. (10) Let $X = Y = \mathbb{Z}$ with the discrete topology. Then the only nontrivial cohomology groups are $H^0(X; \mathbb{Z}) = H^0(Y; \mathbb{Z}) = \mathbb{Z}$. Therefore, it suffices to check the cross product map $H^0(X; \mathbb{Z}) \otimes H^0(Y; \mathbb{Z}) \to H^0(X \times Y; \mathbb{Z})$. Every element in $H^0(\mathbb{Z}; \mathbb{Z})$ simply represents a map $\mathbb{Z} \to \mathbb{Z}$. Then for each $f \in H^0(X; \mathbb{Z}), g \in H^0(Y; \mathbb{Z})$, $f \times g : (a, b) \mapsto f(a)g(b)$. We claim that this is not surjective.

Let δ be the map such that $\delta(i, j) = \delta_{i,j}$. Then clearly, $\delta \in H^0(X \times Y; \mathbb{Z})$. Suppose that there exists $\sum_{i=1}^{n} a^i \otimes b^i$ that gets mapped to δ. Let $a_i, b_i \in \mathbb{Z}^n$ (with subscripts instead of superscripts) denote the vectors $a_i = \langle a^1(i), \cdots, a^n(i) \rangle$, $b_i = \langle b^1(i), \cdots, b^n(i) \rangle$. Then for each $i \in \mathbb{Z}$, the inner product $\langle a_i, b_i \rangle = \delta_{i,j}$. We claim that the set $\{a_i \mid i \in \mathbb{Z}\}$ is linearly independent over $\mathbb{R}$. For simplicity, let $c_1, \cdots, c_m \in \mathbb{R}$ be given such that $\sum_{i=1}^{m} c_i a_i = 0$. (In general, indices could be taken over any finite subset of $\mathbb{Z}$.) This implies $\sum_{i=1}^{m} c_i \delta_{i,j} = 0$ by taking the inner product with b_j for each j. Therefore, we obtain a linearly independent set of infinitely many vectors in $\mathbb{R}^n$. This is clearly impossible, so the cross product map cannot be surjective.