Algebraic Topology Problem Set 5 — Solutions

Q1: Put $g(x) = f(x)/|f(x)|$; as $f(x)$ is never zero, this gives a well-defined, continuous map $g: X \to \mathbb{R}$. If $f(x) > 0$ then $g(x) = 1$, and if $f(x) < 0$ then $g(x) = -1$; thus $g(x)^2 = 1$ for all x. Next, if $t \in I$ and $x \in X$ we certainly have $(1 - t) \geq 0$ and $t|f(x)| \geq 0$. The first of these is only zero when $t = 1$, and the second is only zero when $t = 0$, so the sum is never zero. We can thus define a continuous map $h: I \times X \to \mathbb{R}$ by $h(t, x) = f(x)/((1 - t) + t|f(x)|)$. This is evidently a homotopy between f and g.

Q2:

(a) Define $h: I \times I \to X$ by $h(s, t) = u(st)$. Then $h(1, t) = u(t)$ and $h(0, t) = u(0) = c_{u(0)}(t)$ so h is a homotopy between u and $c_{u(0)}$.

(b) We have seen that $u \simeq c_{u(0)}$ and $v \simeq c_{v(0)}$, so it will suffice to show that $c_{u(0)} \simeq c_{v(0)}$. As X is path-connected, we can choose a path w from $u(0)$ to $v(0)$. We can then define $k: I \times I \to X$ by $k(s, t) = w(s)$. We have $k(0, t) = w(0) = u(0) = c_{u(0)}(t)$ and $k(1, t) = w(1) = v(0) = c_{v(0)}(t)$, so k is the required homotopy.

Q3:

(a) The three pictures show u, v and w.

(b) Just use the linear homotopy: $h(t, x, y) = (1 - t)u(x, y) + tv(x, y)$.

(c) Suppose that $(x, y) \in S^1$. If $u(x, y) \in S^1$ then we must have $y/2 = 0$ and $(x/2 + 1)^2 + 0^2 = 1$. The first of these means that $y = 0$, and $(x, y) \in S^1$ so $x = \pm 1$. This is inconsistent with the equation $(x/2 + 1)^2 + 0^2 = 1$, so we cannot have $u(x, y) \in S^1$ after all, so we must have $u(x, y) \in \mathbb{R}^3 \setminus S^1 = X$. Essentially the same argument works for v and w.

(d) Define $k: I \times S^1 \to \mathbb{R}^3$ by
$$k(t, x, y) = \text{rotation of } u(x, y) \text{ through angle } \pi t \text{ around the } z\text{-axis}$$
$$= (\cos(\pi t)(x/2 + 1), \sin(\pi t)(x/2 + 1), y/2).$$

If $k(t, x, y) \in S^1$ then we must have $y/2 = 0$ and $(\cos(\pi t)(x/2 + 1))^2 + (\sin(\pi t)(x/2 + 1))^2 = 1$. These equations reduce easily to $y = 0$ and $(x/2 + 1)^2 = 1$ so $x = 0$ or $x = -4$. We also have $x^2 + y^2 = 1$ because $(x, y) \in S^1$. This is clearly inconsistent, so we must have $k(t, x, y) \notin S^1$, so k is a map from $I \times S^1$ to X.

As $(\cos(0), \sin(0)) = (1, 0)$ we have $k(0, x, y) = u(x, y)$. As $(\cos(\pi), \sin(\pi)) = (-1, 0)$ we have $k(1, x, y) = v(x, y)$, so k is the required homotopy between u and v.

(e) Define
$$m(t, x, y) = v(\text{ rotation of } (x, y) \text{ through } \pi t)$$
$$= v(\cos(\pi t)x - \sin(\pi t)y, \sin(\pi t)x + \cos(\pi t)y).$$

As $m(t, x, y) = v(\text{something})$ we have $m(I \times S^1) \subseteq v(S^1)$. In particular, we have $m(I \times S^1) \subseteq X$, so $m: I \times S^1 \to X$. We also have $m(0, x, y) = v(x, y)$ and $m(1, x, y) = v(-x, -y) = w(x, y)$, so m is a homotopy between v and w. The equation $v(x, y) = m(0, x, y)$ also tells us that $v(S^1) \subseteq m(I \times S^1)$, so $m(I \times S^1) = v(S^1)$ as required.

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