

## 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  $g: X \rightarrow \mathbb{R}$ . 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  $h: I \times X \rightarrow \mathbb{R}$  by  $h(t, x) = f(x)/((1-t) + t|f(x)|)$ . This is evidently a homotopy between  $f$  and  $g$ .

**Q2:**

- (a) Define  $h: I \times I \rightarrow X$  by  $h(s, t) = s(t)$ . Then  $h(1, t) = u(t)$  and  $h(0, t) = s(t) = c_{u(0)}(t)$  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  $k: I \times I \rightarrow X$  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  $k: I \times S^1 \rightarrow \mathbb{R}^3$  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  $m: I \times S^1 \rightarrow X$ . We also have  $m(0, x, y) = v(x, y)$  and  $m(1, x, y) = v(-x, -y) = u(x, y)$ , so  $m$  is a homotopy between  $v$  and  $u$ . 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.

# Topology Problem Solutions

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