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**METRIC COMPONENTS OF CONTINUOUS IMAGES OF  
ORDERED COMPACTA**

JOSEPH NICHOLAS SIMONE

## METRIC COMPONENTS OF CONTINUOUS IMAGES OF ORDERED COMPACTA

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**In this paper the metric component of each point of a Hausdorff space is defined. Several properties of the metric components of continuous images of ordered compacta are then established.**

A *compactum* is a compact Hausdorff space and a *continuum* is a connected compactum. Any Hausdorff space which can be obtained as a continuous image of an ordered compactum will be called an IOK. Let  $X$  be a Hausdorff space. Define the relation  $\sim$  on  $X$  by  $x \sim y$  if and only if there exists a metric continuum in  $X$  containing  $x$  and  $y$ . For each  $x$  in  $X$ , let  $M_x = \{y \in X | x \sim y\}$ .  $M_x$  is called the *metric component* of  $x$ . In this paper we will study the properties of metric components of connected IOK's. Our first theorem follows immediately from the above definitions.

**THEOREM 1.** *For each Hausdorff space  $X$ ,  $\sim$  is an equivalence relation on  $X$  and  $M_x$  is connected for each  $x$  in  $X$ .*

In general, the metric components of connected IOK's do not have to be compact. This can be seen by considering the "long line." However, under the hypotheses of the next theorem, we obtain the desired result.

**THEOREM 2.** *If  $X$  is a first countable IOK, then  $M_x$  is a continuum for each  $x$  in  $X$ .*

*Proof.* Let  $x \in X$ . We will show that  $M_x$  is closed in  $X$ . Let  $y$  be a limit point of  $M_x$  and let  $\{U_n | n \in N\}$  where  $N$  denotes the set of natural numbers, be a countable base at  $y$ . For each  $n$ , let  $x_n \in U_n \cap M_x$  and let  $K_n$  be a metric subcontinuum of  $X$  containing  $x$  and  $x_n$ . Let  $K = \text{Cl } \bigcup_n K_n$ . Clearly,  $K$  is a continuum and  $x, y \in K$ . Since each  $K_n$  is separable, it follows immediately that  $K$  is separable. However,  $K$  is a closed subset of  $X$ , and therefore  $K$  is a separable connected IOK. It follows that  $K$  is metrizable [8]. Thus,  $y \in M_x$  and hence  $M_x$  is closed.

A space  $X$  is *paraseparable* (*Suslinian*) if each collection of disjoint nonempty open sets (nondegenerate continua) in  $X$  is countable. Every Suslinian continuum is paraseparable [7] and every parase-

parable IOK is first countable [5]. Thus, every Suslinian connected IOK is first countable. If  $S$  is a net whose domain is the directed set  $D$ , then we will use the notation  $\{S_\alpha, \alpha \in D\}$  for  $S$ . When dealing with sequences,  $N$  will always denote the set of natural numbers. If  $X$  is a space and  $A \subseteq B \subseteq X$ , then we will use the notation  $\partial B$  to denote the boundary of  $B$  in  $X$  and the notation  $\partial_B A$  to denote the boundary of  $A$  in the subspace  $B$ .

The following theorem is due to A. J. Ward ([9] and [4]).

**THEOREM 3.** *If  $X$  is an IOK and  $\{F_n, n \in N\}$  is a sequence of disjoint closed subsets of  $X$ , then  $\limsup F_n$  is separable.*

We give a proof for the case when  $X$  is paraseparable, which is all that we require.

*Proof.* Suppose that  $X$  is a paraseparable IOK. Then the boundary of every open subset of  $X$  is separable ([5] and [3]). Now, each  $F_n$  is closed, and therefore  $\partial(X - F_n)$  is separable. Since each  $F_n$  is closed,  $\partial F_n = \partial(X - F_n)$ , and therefore  $\partial F_n$  is separable for every  $n$ . Hence  $\bigcup_n \partial F_n$  is separable and therefore  $\text{Cl} \bigcup_n \partial F_n$  is separable. Let  $F = \text{Cl} \bigcup_n F_n$ . Since  $\{F_n, n \in N\}$  is a sequence of disjoint closed sets, we have that

$$\text{Cl} \bigcup_n F_n = \bigcup_n F_n \cup \limsup F_n .$$

Now,  $F$  is a closed subset of  $X$  and hence  $F$  is a IOK. Thus,  $F$  is paraseparable, and therefore each  $F$ -open set is an  $F_\sigma$  in  $F$  [5]. Let

$$M = \bigcup_n F_n - \limsup F_n .$$

Now,  $F - M = \limsup F_n$ , and hence  $M$  is  $F$ -open. Thus,  $M$  is an  $F_\sigma$  in  $F$ , and therefore  $\partial_F M$  is separable [3]. Furthermore, since  $F$  is closed,  $M \subseteq F$ , and  $M$  is  $F$ -open, it follows that  $\partial_F M = \bar{M} \cap (F - M)$ .

Let

$$S = \text{Cl} \bigcup_n \partial F_n \cup \partial_F M .$$

Since  $S$  is the union of two closed separable subspaces of  $X$ ,  $S$  is a separable IOK. We claim that  $\limsup F_n \subseteq S$ . Suppose that  $x \in \limsup F_n - \partial_F M$ . Then  $x \notin \bar{M}$ . Let  $V$  be an open set such that  $x \in V \subseteq X - \bar{M}$ . There exists an  $n_0$  such that  $V \cap F_{n_0} \neq \emptyset$ . Since  $V \cap (\bigcup_n F_n - \limsup F_n) = \emptyset$ ,  $V \cap (F_{n_0} - \limsup F_n) = \emptyset$ , and hence

$$V \cap F_{n_0} \subseteq \limsup F_n \subseteq \text{Cl}(X - F_{n_0}) .$$

Therefore

$$V \cap (F_{n_0} \cap \text{Cl}(X - F_{n_0})) = V \cap \partial F_{n_0} \neq \emptyset .$$

It follows that  $V \cap \bigcup_n \partial F_n \neq \emptyset$ , and hence  $x \in \text{Cl} \bigcup_n \partial F_n$ . Therefore  $\limsup F_n \subseteq S$ . Since every closed subset of a separable IOK is separable [5], it follows that  $\limsup F_n$  is separable.

**THEOREM 4.** *If  $X$  is a Suslinian connected IOK, and  $Y = \{M_x | x \in X\}$ , then  $Y$  is an upper semi-continuous decomposition of  $X$ .*

*Proof.* By Theorem 2, each  $M_x$  is a continuum. Thus,  $Y$  is certainly a decomposition of  $X$ . Let  $H \in Y$  and let  $U$  be an open set such that  $H \subseteq U$ . Now, since  $X$  is Suslinian and the elements of  $Y$  are disjoint continua,  $Y$  has only countably many nondegenerate members. Let  $\mathcal{S}$  denote the set of all elements  $M$  of  $Y$  such that  $M \cap U \neq \emptyset$  and  $M \not\subseteq U$ . Since each element of  $\mathcal{S}$  is nondegenerate,  $\mathcal{S}$  is countable. Let  $K = \text{Cl} \bigcup \mathcal{S}$ . We claim that  $K \cap H = \emptyset$ . Suppose  $x \in K \cap H$ . Since each element of  $\mathcal{S}$  is disjoint from  $H$ , it follows that  $\mathcal{S}$  is infinite. Let  $\mathcal{S} = \{K_n | n \in N\}$ . Since  $\{K_n, n \in N\}$  is a sequence of disjoint closed sets,

$$\text{Cl} \bigcup_n K_n = \bigcup_n K_n \cup \limsup K_n .$$

Since  $H \cap K_n = \emptyset$  for each  $n$ , it follows that  $x \in H \cap \limsup K_n$ . Let  $\{U_n | n \in N\}$  be a monotone decreasing countable base at  $x$ . Clearly, there exists a subsequence  $\{K_{n_i}, i \in N\}$  of  $\{K_n, n \in N\}$  such that  $K_{n_i} \cap U_i \neq \emptyset$  for all  $i$ . It follows that  $x \in \liminf K_{n_i}$ . Thus,  $\limsup K_{n_i}$  is a continuum. By Theorem 3,  $\limsup K_{n_i}$  is separable and therefore  $\limsup K_{n_i}$  is a metrizable continuum [8]. Now, for each  $K_{n_i}, K_{n_i} \not\subseteq U$ , so that  $K_{n_i} \cap (X - U) \neq \emptyset$ . Since  $X - U$  is compact, there exists a  $y$  in  $X - U$  such that  $y \in \limsup K_{n_i}$ . Thus,  $\limsup K_{n_i}$  is a metric continuum containing  $x$  and  $y$ . However, this is impossible since  $H$  is the metric component of  $x, H \subseteq U$ , and  $y \notin U$ . It follows that  $K \cap H = \emptyset$ . Let  $V = U - K$ . Then  $V$  is an open set, and, clearly,  $H \subseteq V \subseteq U$ . Let  $L \in Y$  such that  $L \cap V \neq \emptyset$ . Then,  $L \cap U \neq \emptyset$ , and since  $V = U - \text{Cl} \bigcup_n K_n$ , it follows that  $L \subseteq U$ . Thus,  $Y$  is upper semi-continuous.

Whenever  $\{A | A \in Y\}$  is a decomposition of  $X$ , it is to be assumed that  $Y$  is given the quotient topology derived from the topology of  $X$ , and that  $p$  denotes the natural map from  $X$  onto  $Y$  given by  $p(x) = A$  where  $x \in A \in Y$ .

**THEOREM 5.** *Let  $X$  be a Suslinian connected IOK and let  $Y =$*

$\{M_x | x \in X\}$ . If  $K$  is a subcontinuum of  $Y$ , then  $p^{-1}(K)$  is a subcontinuum of  $X$ .

*Proof.* Let  $K$  be a subcontinuum of  $Y$ , and let  $K^* = p^{-1}(K)$ . Since  $Y$  is upper semi-continuous,  $p$  is continuous and closed. Thus,  $K^*$  is a compact subset of  $X$ . Suppose that  $K^*$  is not connected. Then  $K^*$  is the union of two disjoint closed subsets  $A^*$  and  $B^*$  of  $X$ . Let  $A = p(A^*)$  and  $B = p(B^*)$ . Then  $A$  and  $B$  are closed subsets of  $Y$  and  $A \cup B = K$ . Since  $K$  is connected we must have that  $A \cap B \neq \emptyset$ . Let  $M_x \in A \cap B$ . Then  $M_x \in p(A^*) \cap p(B^*)$ , and hence there exist an  $a$  in  $A^*$  and a  $b$  in  $B^*$  such that  $p(a) = p(b) = M_x$ . Thus,  $M_x \subseteq K^* = A^* \cup B^*$ . But  $M_x \cap A^* \neq \emptyset$  and  $M_x \cap B^* \neq \emptyset$ , which contradicts the fact that  $M_x$  is connected. Therefore  $K^*$  is a continuum.

**THEOREM 6.** *If  $X$  is a Suslinian connected IOK, then  $M_x$  is metrizable for each  $x$  in  $X$ .*

*Proof.* Let  $x \in X$ . If  $M_x = \{x\}$ , then, clearly,  $M_x$  is metrizable. So suppose that  $M_x$  is nondegenerate. Let  $\mathcal{S}$  denote the set of all collections of disjoint nondegenerate metric continua contained in  $M_x$ . Clearly,  $\mathcal{S} \neq \emptyset$ . By Zorn's Lemma it follows immediately that  $\mathcal{S}$  has a maximal element  $\mathcal{M}$ . Since  $X$  is Suslinian,  $\mathcal{M}$  is countable. Let  $\mathcal{M} = \{M_n | n \in N'\}$ , where  $N'$  is some subset of  $N$ .

Now, since each  $M_n$  is a metric continuum, each  $M_n$  has a countable dense subset  $D_n$ . Let  $D = \bigcup_n D_n$ . Then  $D$  is countable. We claim that  $D$  is dense in  $M_x$ . Suppose that  $y \in M_x - D$ . By definition there exists a metric continuum  $K$  such that  $y \in K \subseteq M_x$  and  $K \cap D \neq \emptyset$ . Let  $U$  be any open set containing  $y$  and let  $V$  be an open set such that  $y \in V$ ,  $\bar{V} \subseteq U$  and  $K \cap (X - V) \neq \emptyset$ . Then  $K \cap V$  is a proper  $K$ -open set. Let  $C$  be the component of  $y$  in  $K \cap V$ . Then  $\bar{C} \cap \partial_K(K \cap V) \neq \emptyset$  [2], and hence  $\bar{C}$  is a nondegenerate subcontinuum of  $M_x$ . Furthermore,  $\bar{C} \subseteq K$  and therefore,  $\bar{C}$  is metric. Since  $\mathcal{M}$  is maximal,  $\bar{C} \cap M_n \neq \emptyset$  for some  $n$ . However,  $\bar{C} \subseteq U$ , and hence  $U \cap M_n \neq \emptyset$ . But then  $U \cap D \neq \emptyset$ , so  $y \in \bar{D}$ . Thus,  $D$  is dense in  $M_x$ . Since  $M_x$  is a connected IOK, it follows that  $M_x$  is metrizable [8].

A continuum  $X$  is *netlike* if each pair of points in  $X$  can be separated by a finite set. The following theorem is proved in [7].

**THEOREM 7.** *If  $X$  is a paraseparable continuum containing no nondegenerate metric subcontinuum, then  $X$  is netlike if and only if it is an IOK.*

**THEOREM 8.** *If  $X$  is a Suslinian connected IOK, and  $Y = \{M_x | x \in X\}$ , then  $Y$  is a netlike continuum.*

*Proof.* Let  $Y = \{M_x | x \in X\}$ . Then  $Y$  is an upper semi-continuous decomposition of  $X$  and  $Y$  is a continuum. Let  $p$  be the natural map from  $X$  onto  $Y$ . Since  $Y$  is upper semi-continuous,  $p$  is continuous and closed. It follows from Theorem 5 that  $Y$  is Suslinian. Therefore  $Y$  is a paraseparable connected IOK.

We claim that  $Y$  contains no nondegenerate metric subcontinuum. Suppose that  $K$  is a nondegenerate metric subcontinuum of  $Y$ . Let  $H = p^{-1}(K)$ . By Theorem 5,  $H$  is a nondegenerate subcontinuum of  $X$ . Now, since  $X$  is Suslinian,  $Y$  has only countably many nondegenerate members. Let  $\{p(x_n) | n \in N'\}$ , where  $N' \subseteq N$ , denote the set of nondegenerate elements of  $Y$  contained in  $H$ . By Theorem 6, each  $M_{x_n}$  is a metric continuum and hence contains a countable dense set  $D_n$ . Now,  $K$  is a metric subcontinuum of  $Y$ , and hence  $K$  has a countable dense subset  $E$ . Let  $F = E - \{p(x_n) | n \in N'\}$ . Thus, if  $M_x \in F$ , then  $M_x = \{x\}$ . Let  $A = p^{-1}(F)$ . Then  $A$  is a countable subset of  $X$ . Let  $D = A \cup \bigcup_n D_n$ .  $D$  is a countable set. We claim that  $D$  is dense in  $H$ . Let  $U$  be an  $H$ -open set. If  $U \cap M_{x_n} \neq \emptyset$  for some  $n$ , then  $U \cap D_n \neq \emptyset$  and therefore  $U \cap D \neq \emptyset$ . Suppose that  $U \cap M_{x_n} = \emptyset$  for each  $n$ . Thus, if  $x \in U$ , then  $p(x) = \{x\}$  and therefore  $p^{-1}(p(U)) = U$ . Hence

$$p(H - U) = p(H) - p(U) = K - p(U).$$

Now, since  $H - U$  is a closed set and  $p$  is a closed map,  $K - p(U)$  is closed. Thus,  $p(U)$  is  $K$ -open. Hence  $p(U) \cap E \neq \emptyset$ . However,  $x \in U$  implies that  $p(x) = \{x\}$ , and therefore  $p(U) \cap F \neq \emptyset$ . Let  $\{y\} \in p(U) \cap F$ . Then  $y \in A$  and  $y \in p^{-1}(p(U)) = U$ , so that  $U \cap A \neq \emptyset$ . Thus,  $U \cap D \neq \emptyset$ , and therefore  $D$  is dense in  $H$ . Since  $H$  is a separable connected IOK,  $H$  is metrizable, and therefore  $p(H) = K$  is degenerate. Hence  $Y$  contains no nondegenerate metric subcontinuum. By Theorem 7,  $Y$  is netlike.

An *hereditarily locally connected* continuum is a continuum in which each subcontinuum is locally connected. By combining Theorems 4, 6 and 8 we immediately obtain the following result.

**THEOREM 9.** *If  $X$  is a Suslinian connected hereditarily locally connected IOK, then there exists an upper semi-continuous decomposition  $Y$  of  $X$  such that the space  $Y$  is a netlike continuum and each element of  $Y$  is a Peano space.*

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