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Limiting subcontinua and Whitney maps of tree-like continua

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Abstract. It is known that if X is a tree-like continuum and ω is any Whitney map for $C(X)$, then the Whitney continuum $\omega^{-1}(t)$ is an FAR for each $0 \leq t \leq \omega(X)$ (see [5] or [17]). In this paper, we define limiting subcontinua of a continuum and we prove the following: Let X be a tree-like continuum and let ω be any Whitney map for $C(X)$. Then for each $0 \leq t \leq \omega(X)$, the following are equivalent:

- (1) $\omega^{-1}(t)$ is an absolute retract (= AR).
- (2) $\omega^{-1}(t)$ is a Peano continuum
- (3) $t \geq \sup \{\omega(L) \mid L \text{ is a limiting subcontinuum of } X\}$.

1. Introduction

Let X be a continuum and let ω be any Whitney map for $C(X)$. It is known that if X is a tree-like continuum, then the Whitney continuum $\omega^{-1}(t)$ is an FAR for each $0 \leq t \leq \omega(X)$ (see [5] or [17]). Also, if X is a dendrite (= locally connected tree-like continuum), then $\omega^{-1}(t)$ is an AR for each $0 \leq t \leq \omega(X)$ (see [19]). In this paper, we consider the following question: Let X be a tree-like continuum and let ω be any Whitney map for $C(X)$. What is the smallest number $I(\omega) \geq 0$ such that $\omega^{-1}(I(\omega))$ is an AR? Note that $\omega^{-1}(\omega(X)) = \{X\}$ is an AR. If X is a hereditarily indecomposable tree-like continuum, then $\omega^{-1}(t)$ is also a hereditarily indecomposable tree-like continuum for each $0 \leq t < \omega(X)$ (see [13]), hence $I(\omega) = \omega(X)$. On the other hand, it is easily seen that there is a tree-like continuum X such that $0 < I(\omega) < \omega(X)$. For example, consider the following set X in the plane E^2 :

$$X = \{(X, \sin 1/x) \in E^2 \mid 0 < x \leq 1\} \cup \{(0, y) \in E^2 \mid -1 \leq y \leq 1\}.$$

Then $0 < I(\omega) = \omega(\{(0, y) \in E^2 \mid -1 \leq y \leq 1\}) < \omega(X)$.

In this paper, we define limiting subcontinua of a continuum and we prove the following: Let X be a tree-like continuum and let ω be any Whitney map for $C(X)$. Then for each $0 \leq t \leq \omega(X)$, the following are equivalent:

- (1) $\omega^{-1}(t)$ is an AR.
- (2) $\omega^{-1}(t)$ is a Peano continuum.
- (3) $t \geq \sup \{\omega(L) | L \text{ is a limiting subcontinuum of } X\}$.

Hence $I(\omega) = \sup \{\omega(L) | L \text{ is a limiting subcontinuum of } X\}$.

All spaces considered in this paper are assumed to be metric spaces. A *continuum* is a compact connected space. We denote by $C(X)$ the *hyperspace* of all nonempty subcontinua of a continuum X with the Hausdorff metric ϱ_H . Given a continuum X , a *Whitney map* ω for $C(X)$ (see [18] and [21]) is a map from $C(X)$ into $[0, \infty)$ satisfying $\omega(\{x\}) = 0$ for each $x \in X$ and $\omega(A) < \omega(B)$ if $A, B \in C(X)$, $A \subset B$ and $A \neq B$. It is well-known that such a map $\omega: C(X) \rightarrow [0, \omega(X)]$ is a monotone map. Then the continua $\omega^{-1}(t)$ ($0 \leq t < \omega(X)$) are called *Whitney continua*. A continuum X is a *tree-like continuum* if for any $\varepsilon > 0$, there is an onto map $f: X \rightarrow T$ such that T is a (polyhedral) tree and $\text{diam } f^{-1}(y) < \varepsilon$ for each $y \in T$.

We refer readers to [18] for hyperspace theory.

2. Limiting subcontinua of a continuum

Let X be a continuum. A subcontinuum L of X is said to be a *limiting subcontinuum* of X provided that one of the following conditions (1) and (2) holds.

- (1) L is a one point set.
- (2) There is an open set $U \supset L$ of X and a sequence $\{L_n\}$ of subcontinua in U such that $\lim L_n = L$ and $A_n \cap A_m = \emptyset$ ($n \neq m$), where A_n is the component of $Cl U$ containing L_n for each n .

Set $L(X) = \{L \in C(X) | L \text{ is a limiting subcontinuum of } X\}$. Note that $L(X) \supset F_1(X) = \{\{x\} | x \in X\}$ and $L(X)$ does not contain X .

The following propositions are easily seen. Hence we omit the proofs.

(2.1) PROPOSITION. *If $L \in L(X)$ and L is nondegenerate, then there is $L' \in L(X)$ such that $L \subset L'$ and $L \neq L'$.*

(2.2) PROPOSITION. *A continuum X is a Peano continuum if and only if $L(X) = F_1(X)$.*

Now, we prove the following

(2.3) PROPOSITION. *Let X be a continuum and let ω be any Whitney map for $C(X)$. Then for each $0 \leq t \leq \omega(X)$, the following are equivalent.*

- (1) $\omega^{-1}(t)$ is a Peano continuum.
- (2) $\omega^{-1}([t, \omega(X)])$ is a Peano continuum.
- (3) $t \geq \sup \{\omega(L) \mid L \in L(X)\}$.

To prove (2.3), we need the following (cf. [14, (2.3)]).

(2.4) LEMMA. *Let $A \in \omega^{-1}(t)$ ($0 \leq t \leq \omega(X)$) and $\varepsilon > 0$. Then there are a neighborhood $U(t)$ of A in X and numbers t_0 and t_1 such that $t_0 < t < t_1$ and if $B \in U^*(t) \cap \omega^{-1}([t_0, t_1])$, then $\varrho_H(A, B) < \varepsilon$, where $U^*(t) = \{D \in C(X) \mid D \subset U(t)\}$.*

Proof of (2.3). We shall show that (3) implies (1). Let $A \in \omega^{-1}(t)$ and $\varepsilon > 0$. By (2.4), there is a neighborhood $U(t)$ of A in X satisfying the condition of (2.4). Let A' be the component of $Cl U(t)$ which contains A . Set $W(A) = C(A') \cap \omega^{-1}(t)$. We shall show that $W(A)$ is a neighborhood of A in $\omega^{-1}(t)$. Suppose, on the contrary, that there is a sequence $\{L_n\}$ of points of $\omega^{-1}(t)$ such that L_n is not contained in $W(A)$ for each n and $\lim L_n = A$. Since $U^*(t) \cap \omega^{-1}(t)$ is an open set in $\omega^{-1}(t)$, we may assume that $L_n \subset U(t)$ for all n . Note that $L_n \cap A' = \phi$ for each n . Let A_n be the component of $Cl U(t)$ containing L_n . Since $L_n \cap A' = \phi$, $A_n \cap A' = \phi$. Hence $A_n \cap A_m = \phi$ ($n \neq m$). Then $A \in L(X)$. By (2.1), there is $L \in L(X)$ such that $A \subset L$ and $A \neq L$, which implies that $t = \omega(A) < \omega(L) < \sup \{\omega(L) \mid L \in L(X)\} \leq t$. This is a contradiction. Hence $W(A)$ is a neighborhood of A in $\omega^{-1}(t)$. Note that $W(A)$ is a continuum and $\text{diam } W(A) < 2\varepsilon$ (see (2.4)). This implies that $\omega^{-1}(t)$ is a Peano continuum.

Next, we shall show that (1) implies (3). Suppose, on the contrary, that $0 \leq t < \sup \{\omega(L) \mid L \in L(X)\}$. Then there is $L \in L(X)$ such that $\omega(L) > t$. Then there are a neighborhood U of L in X and a sequence $\{L_n\}$ of subcontinua of X such that $\lim L_n = L$, $L_n \subset U$ and $A_n \cap A_m = \phi$ ($n \neq m$), where A_n denotes the component of $Cl U$ containing L_n . We may assume that $\omega(L_n) > t$ for all n . Choose $B_n \in \omega^{-1}(t)$ with $B_n \subset L_n$ for each n . We may assume that $\lim B_n = B \subset L$. Since $\omega^{-1}(t)$ is locally connected, there are continua α_n ($n \geq n_0$) of $\omega^{-1}(t)$ such that $B, B_n \in \alpha_n$ and $D_n = \cup \{E \in \alpha_n\} \subset U$. Then D_n is a continuum containing B_n and B ($n \geq n_0$) (see [13]). Hence $A_n \cap A_m \neq \phi$ ($m, n \geq n_0$). This is a contradiction. The remainder of the proof is similar and will be omitted.

(2.5) COROLLARY. *Let X be a chainable continuum (resp. a proper circle-like continuum) and let ω be any Whitney map for $C(X)$. Then for any $t > 0$, the following are equivalent.*

- (1) $\omega^{-1}(t)$ is an arc or a one point set (resp. a circle or a one point set).
- (2) $t \geq \sup \{\omega(L) \mid L \in L(X)\}$.

Proof. By J. Krasinkiewicz [14], for any $0 \leq t' < \omega(X)$, $\omega^{-1}(t)$ is a chainable (resp. circle-like) continuum. Hence (2.5) follows from (2.3).

In [15], J. Krasinkiewicz and S.B. Nadler proved that the property of being an indecomposable chainable continuum is a Whitney property, and if X is a decomposable chainable continuum, then there is $t_0 < \omega(X)$ such that $\omega^{-1}(t)$ is an arc for each $t_0 \leq t < \omega(X)$. Also, they proved that if X is a decomposable proper circle-like continuum, then there is $t_0 < \omega(X)$ such that $\omega^{-1}(t)$ is a circle for each $t_0 \leq t < \omega(X)$. Hence we have

(2.6) COROLLARY. (1) *Let X be a chainable continuum. Then X is decomposable if and only if X is not contained in the closure of $L(X)$ in $C(X)$.* (2) *If X is a decomposable circle-like continuum, then X is not contained in the closure of $L(X)$ in $C(X)$.*

(2.7) EXAMPLE. There is a decomposable tree-like continuum X such that X is contained in the closure of $L(X)$ in $C(X)$. Let P be a pseudo-arc from p to q in the plane E^2 and let U be an open set of P such that $\dim \text{Fr}_X U = 0$, $p \in U$ and $q \in \text{Int}_X (P - U)$. Set $X = P \cup (\text{Fr}_X U \times [-1, 1]) \subset E^3$. Then X is a decomposable tree-like continuum. We can check that X is contained in the closure of $L(X)$ in $C(X)$.

3. Whitney continua of a tree-like continuum which are ARs

In this section, we prove the following main result in this paper.

(3.1) THEOREM. *Let X be a tree-like continuum and let ω be any Whitney map for $C(X)$. Then for each $0 \leq t \leq \omega(X)$, the following are equivalent.*

- (1) $\omega^{-1}(t)$ is an AR.
- (2) $\omega^{-1}([t, \omega(X)])$ is an AR.
- (3) $\omega^{-1}(t)$ is a Peano continuum.
- (4) $\omega^{-1}([t, \omega(X)])$ is a Peano continuum.
- (5) $t \geq \sup \{\omega(L) \mid L \in L(X)\}$.

Let X be a continuum contained in a metric space M . Then X is weak homotopically trivial within small neighborhoods of M provided that if

$f: S^n \rightarrow X$ is any map from the n -sphere S^n ($n \geq 0$) to X , f is null-homotopic in any neighborhood of X in M . Note that if X is an FAR (see [1] for the definition of FAR), then X is weak homotopically trivial within small neighborhoods of any ANR M which contains X . Let X be a continuum contained in a metric space M . We may assume that $\text{diam } X < 1$. Then we consider the following property; (*) there exists a sequence $\{\mathcal{V}_n\}_{n=0,1,2,\dots}$ of finite closed coverings of X such that (i) $\mathcal{V}_0 = \{X\}$, and $X = \cup \{\text{Int}_X V \mid V \in \mathcal{V}_n\}$ for each n , (ii) $\text{mesh } \mathcal{V}_n < 1/2^n$ for each n , and (iii) if $V_\alpha \in \mathcal{V} = \cup \mathcal{V}_n$ and $\cap V_\alpha \neq \phi$, then $\cap V_\alpha$ is weak homotopically trivial within small neighborhoods of M (cf. [16]). Note that if $\cap V_\alpha \neq \phi$, then $\cap V_\alpha$ has the property (*).

The key lemma is the following:

(3.2) LEMMA. *Let X be a continuum contained in a metric space M . If X has the property (*), then X is an AR.*

Proof. Let $\{\mathcal{V}_n\}$ be a sequence of closed coverings of X satisfying the property (*). First, we shall prove that X is k -connected for each $k = 0, 1, 2, \dots$. Since each intersection W of V 's of $\mathcal{V} = \cup \mathcal{V}_n$ has the property (*), the fact that X is k -connected implies that W is k -connected. We will show that X is 0-connected. Since each element V of \mathcal{V} is connected, the conditions (i) and (ii) implies that X is a Peano continuum. Hence X is 0-connected. Next, we assume that X is $(k - 1)$ -connected ($k \geq 1$). Then each intersection of V 's of \mathcal{V} is also $(k - 1)$ -connected. We must show that X is k -connected. Let $f: \hat{\Delta} \rightarrow X$ be a map, where Δ denotes a $(k + 1)$ -simplex and $\hat{\Delta}$ denotes the boundary of Δ . Now, we will construct a sequence $\{f_n\}_{n=0,1,2,\dots}$ of maps from Δ to M and a sequence $\{\mathcal{T}_n\}_{n=0,1,2,\dots}$ of triangulations of Δ such that

- (1) \mathcal{T}_0 is the standard triangulation of Δ and \mathcal{T}_{n+1} is a subdivision of \mathcal{T}_n ,
- (2) $f_n(L_n) \subset X$, where L_n denotes the k -skeleton of \mathcal{T}_n , i.e., $L_n = |\mathcal{T}_n^k|$,
- (3) $f_0|_{\hat{\Delta}} = f$ and $f_{n+1}|_{L_n} = f_n|_{L_n}$ for each n ,
- (4) (f_n, \mathcal{T}_n) is normed by \mathcal{V}_n , i.e., for any $(k + 1)$ -simplex σ of \mathcal{T}_n , there is some $V \in \mathcal{V}_n$ such that $f_n(\hat{\sigma}) \subset V$ and $f_n(\sigma) \subset N(V)$, where $N(V)$ is a neighborhood of V in M such that $\text{diam } N(V) < 1/2^n$ (see (ii)), and
- (5) if σ is a $(k + 1)$ -simplex of \mathcal{T}_n and $V \in \mathcal{V}_n$ is as in (4), then for any $(k + 1)$ -simplex σ' of \mathcal{T}_{n+1} with $\sigma' \subset \sigma$, $f_{n+1}(\sigma') \subset N(V)$.

Note that $L_0 = \hat{\Delta}$. Since X is weak homotopically trivial within small neighborhoods of M , we have an extension $f_0: \Delta \rightarrow N(X)$ of f , where $N(X)$ is a neighborhood of X in M such that $\text{diam } N(X) < 1/2^0$. Clearly, f_0 satisfies the conditions (1)–(5). Suppose that we have maps f_0, f_1, \dots, f_{n-1}

which satisfy the conditions (1)–(5). We will construct the desired map f_n as follows: For each $(k + 1)$ -simplex σ of \mathcal{T}_{n-1} , there is some $V \in \mathcal{V}_{n-1}$ satisfying the condition (4), i.e., $f_{n-1}(\dot{\sigma}) \subset V$ and $f_{n-1}(\sigma) \subset N(V)$.

Consider the following set

$$\mathcal{V}_n(\sigma) = \{V' \cap V \mid V' \cap V \neq \phi, V' \in \mathcal{V}_n\}.$$

For each $W = V' \cap V \in \mathcal{V}_n(\sigma)$, choose a closed subset $N(W)$ of M such that $N(W) \cap V = W$, $\text{diam } N(W) < 1/2^n$ and $\cup\{\text{Int}_M N(W) \mid W \in \mathcal{V}_n(\sigma)\}$ is a neighborhood of V in $N(V)$. We may assume that $N(W_1) \cap \dots \cap N(W_i) \neq \phi$ if and only if $W_1 \cap \dots \cap W_i \neq \phi$ for $W_1, \dots, W_i \in \mathcal{V}_n(\sigma)$. Since V is weak homotopically trivial within small neighborhoods of M , there is an extension $g_\sigma: \sigma \rightarrow \cup\{\text{Int}_M N(W) \mid W \in \mathcal{V}_n(\sigma)\}$ of $f_{n-1}|_{\dot{\sigma}}$. Choose a subdivision \mathcal{T}_n of \mathcal{T}_{n-1} such that if σ' is a $(k + 1)$ -simplex of \mathcal{T}_n and $\sigma' \subset \sigma \in \mathcal{T}_{n-1}$, then $g_\sigma(\sigma') \subset N(W)$ for some $W \in \mathcal{V}_n(\sigma)$. If P is a vertex of \mathcal{T}_n and $P \in \sigma - \dot{\sigma}$ ($\sigma \in \mathcal{T}_{n-1}$), we choose a point $h(P) \in \cap\{W \in \mathcal{V}_n(\sigma) \mid g_\sigma(P) \in N(W)\}$. Hence we have a map $h: L_{n-1} \cup |\mathcal{T}_n^0| \rightarrow M$ such that $h|_{L_{n-1}} = f_{n-1}|_{L_{n-1}}$. Since $\cap\{W \in \mathcal{V}_n(\sigma) \mid h((L_{n-1} \cap \tau) \cup \tau^0) \subset W\}$ is $(k - 1)$ -connected for any $\tau \in \mathcal{T}_n^k$ with $\tau \subset \sigma$ (where σ is a $(k + 1)$ -simplex of \mathcal{T}_{n-1} and τ^0 denotes the 0-skeleton of τ), by induction we can easily see that there is an extension $h': L_n \rightarrow X$ of h such that if σ' is a $(k + 1)$ -simplex of \mathcal{T}_n and $\sigma' \subset \sigma \in \mathcal{T}_{n-1}$, then $h'(\dot{\sigma}') \subset W$, where $W \in \mathcal{V}_n(\sigma)$ with $g_\sigma(\sigma') \subset N(W)$. Since $W \in \mathcal{V}_n(\sigma)$ is weak homotopically trivial within small neighborhoods of M , there is a map $f_n: \Delta \rightarrow M$ such that $f_n|_{L_n} = h'$ and if σ' is $(k + 1)$ -simplex of \mathcal{T}_n and $\sigma' \subset \sigma \in \mathcal{T}_{n-1}$, then $f_n(\dot{\sigma}') \subset W$ and $f_n(\sigma') \subset N(W)$ for some $W \in \mathcal{V}_n(\sigma)$ with $g_\sigma(\sigma') \subset N(W)$. Clearly, (f_n, \mathcal{T}_n) is normed by \mathcal{V}_n . Also, f_n satisfies the desired conditions. Hence we obtain a sequence $\{f_n\}$ of maps from Δ to M such that $\{f_n\}$ satisfies the conditions (1)–(5). By (4) and (5), we see that $\{f_n\}$ is a Cauchy sequence of maps. Set $F = \lim f_n$. By (4), we can conclude that $F(\Delta) \subset X$. Also, by (3) $F|\dot{\Delta} = f$. Hence X is k -connected, which implies that each intersection of V 's of $\mathcal{V} = \cup \mathcal{V}_n$ is k -connected. Finally, we shall show that X is an AR. Let \mathcal{U} be any open covering of X . By (ii), we may assume that \mathcal{V}_1 is a refinement of \mathcal{U} . Let K be a simplicial complex and let L be a subcomplex of K such that $K^0 \subset L$. Let $f: |L| \rightarrow X$ be a partial realization of K in X relative \mathcal{V}_1 , i.e., for each simplex σ of K , there is some $V \in \mathcal{V}_1$ such that $f(|L| \cap \sigma) \subset V$ (see [2] and [3]). By using the fact that each intersection of V 's of \mathcal{V}_1 is k -connected for all $k = 0, 1, 2, \dots$, we can easily see that there is a full realization $F: |K| \rightarrow X$ of f in X relative \mathcal{V}_1 such that if $\sigma \in K$, then $F(\sigma) \subset \cap\{V \in \mathcal{V}_1 \mid f(|L| \cap \sigma) \subset V\}$. By [2] or [3], X is an ANR. Since

X is k -connected for all $k = 0, 1, 2, \dots$, X is an AR. This completes the proof.

Proof of (3.1). We shall prove that (5) implies (1). Suppose that $t \geq \sup \{\omega(L) \mid L \in L(X)\}$. We shall show that $\omega^{-1}(t)$ has the property (*). Note that $\omega^{-1}(t)$ is an FAR (see [5] or [17]). Hence $\omega^{-1}(t)$ is weak homotopically trivial within small neighborhoods of Q , where Q is the Hilbert cube which contains $\omega^{-1}(t)$. Let $\varepsilon > 0$. As in the proof of (2.3), if $A \in \omega^{-1}(t)$, then $W(A) = C(A') \cap \omega^{-1}(t)$ is a closed neighborhood of A in $\omega^{-1}(t)$ such that $\text{diam } W(A) < 2\varepsilon$. Suppose that $A_\alpha \in \omega^{-1}(t)$ and $\cap W(A_\alpha) \neq \phi$. Note that

$$\cap W(A_\alpha) = \cap C(A'_\alpha) \cap \omega^{-1}(t) = C(\cap A'_\alpha) \cap \omega^{-1}(t).$$

Since X is a tree-like continuum, $\cap A'_\alpha$ is also a tree-like continuum. Hence $\cap W(A_\alpha)$ is an FAR (see [5] or [17]). Hence we can conclude that $\omega^{-1}(t)$ has the property (*). By (3.2), $\omega^{-1}(t)$ is an AR. In a similar way, we can see that (5) implies (2). The remainder of the proof follows from (2.3).

(3.3) COROLLARY. *If X is a tree-like continuum and ω is any Whitney map for $C(X)$, then $\omega^{-1}(t)$ is contractible for $t \geq \sup \{\omega(L) \mid L \in L(X)\}$.*

(3.4) EXAMPLE. Consider the following points in the plane E^2 . $p = (3, 0)$, $q = (-2, 0)$, $p' = (-1, 0)$, $q' = (1, 0)$, $p_n = (-1, -1/n)$ and $q_n = (1, 1/n)$ ($n = 1, 2, \dots$). Let $X = [p, q] \cup \bigcup_{n=1}^\infty [p, p_n] \cup \bigcup_{n=1}^\infty [q, q_n]$, where $[x, y]$ denotes the segment from x to y in E^2 , $x, y \in E^2$. Then X is a dendroid (= path-connected tree-like continuum).

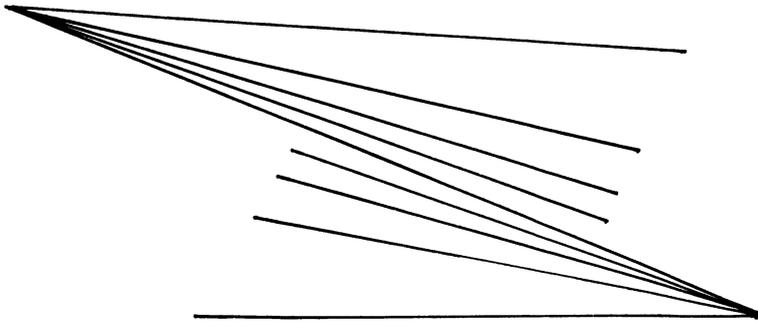


Fig. 1.

Let ω be any Whitney map for $C(X)$. It is easily seen that $\sup \{\omega(L) \mid L \in L(X)\} = \max \{\omega([p, p']), \omega([q, q'])\}$.

(a) $0 < t \leq \omega([p', q'])$.

$\omega^{-1}(t)$:

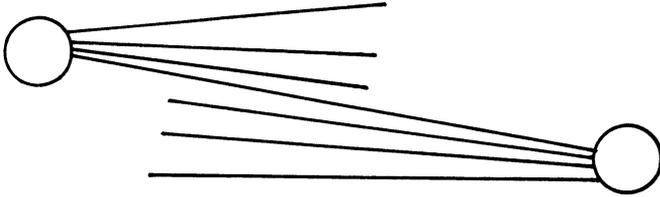


Fig. 2.

(b) $\omega([p', q']) < t \leq \min \{\omega([p, p']), \omega([q, q'])\}$.

$\omega^{-1}(t)$:

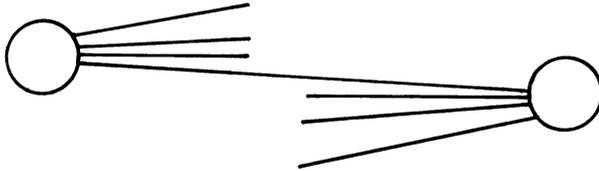


Fig. 3.

(c) $\min \{\omega([p, p']), \omega([q, q'])\} \leq t < \max \{\omega([p, p']), \omega([q, q'])\}$.

$\omega^{-1}(t)$:



Fig. 4.

(d) $\max \{\omega([p, p']), \omega([q, q'])\} \leq t < \omega([p, q])$.

$\omega^{-1}(t)$:



Fig. 5.

(e) $\omega([p, q]) \leq t < \omega(X)$.

$\omega^{-1}(t)$:

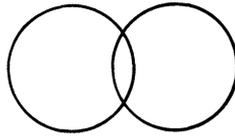


Fig. 6.

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