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FANS AND EMBEDDINGS IN THE PLANE

LEX GERARD OVERSTEEGEN

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We prove that every fan which is locally connected at its vertex can be embedded in the plane. This gives a solution to a problem raised by J. J. Charatonik and Z. Rudy.

1. Introduction and definitions. In 1963, K. Borsuk [4] constructed a fan which is not embeddable in the plane. Hence, the question arises to characterize those fans which are embeddable in the plane. In particular, in [5] it was asked whether each contractible fan is embeddable in the plane. In an attempt to solve this problem in the negative, J. J. Charatonik and Z. Rudy constructed a contractible fan which is locally connected at its vertex. They conjectured ([6], p. 215) that this fan is not embeddable in the plane. We show in this paper that each fan, which is locally connected at its vertex, is embeddable in the plane (see Theorem 5.2). We will also establish, for fans, several equivalences between the local connectedness at the vertex and other conditions. In a forthcoming paper [11] the author has shown that each contractible fan is locally connected at its vertex, and hence embeddable in the plane.

By a *continuum* we mean a compact connected metric space. A *dendroid* is an arc-wise connected and hereditarily unicoherent continuum. By a *fan* we understand a dendroid which has exactly one branch-point, and we call this branch-point the *vertex* of the fan. If x, y are points in a dendroid X , then we denote by $[x, y]$ the unique arc in X having x and y as end-points. The weak-cut order \leq , with respect to a point p , in a dendroid X is given by

$$x \leq y \text{ if and only if } [p, x] \subset [p, y].$$

We denote by I the unit closed interval $[0, 1]$ of reals, and the symbol $B(x, \varepsilon)$ denotes the open ball of radius ε about the point x . We use the symbol \cong to denote that two spaces are homeomorphic. The symbol R , as used in Lemma 3.1, denotes a set of indices.

2. Embeddings in the plane. A cover $U = \{U_1, U_2, \dots, U_n\}$ of a space is called an ε -chain if the nerve (see [8], p. 318) of U is an arc and $\text{diam}(U_i) < \varepsilon$ for $i = 1, 2, \dots, n$. A continuum X is said to be *arc-like* if for each $\varepsilon > 0$ there exists an ε -chain covering X . A point e of an arc-like continuum X is called an *end-point* provided for each $\varepsilon > 0$ there exists an ε -chain U_1, U_2, \dots, U_n covering X such that

$$(1) \quad e \in U_1 \setminus \bigcup_{i=2}^n U_i.$$

It is known (see [9], p. 148) that every 0-dimensional compact metric space K is homeomorphic to a subset of the Cantor ternary set $C \subset [0, 1]$, and hence K possesses a natural order \leq . We will call this ordering the *induced ordering* on K . The main result of this section is Theorem 2.2. We start with the following lemma.

LEMMA 2.1. *Let X be a compact metric space and let $\{J_\alpha\}$, $\alpha \in A$, be the decomposition of X into components. Let $\varepsilon > 0$ and let K be a 0-dimensional compact set in X , with induced ordering \leq such that:*

(2) J_α is an arc-like continuum for each $\alpha \in A$,

(3) $J_\alpha \cap K = \{e_\alpha\}$, where e_α is an end-point of J_α for each $\alpha \in A$.

Then there exists an open cover U of X such that U is a finite union of disjoint ε -chain V_i ($i = 1, 2, \dots, t$), where $V_i = \{U(i, j)\} (j = 1, 2, \dots, k(i))$ such that:

(4) $K \subset \bigcup_{i=1}^t U(i, 1) \setminus \bigcup_{j=2}^{k(i)} U(i, j)$,

(5) all nonadjacent elements of U have positive distance,

(6) for each i , $1 \leq i \leq t$, there exist $a_i, b_i \in K$ such that:

$$K \cap U(i, 1) = \{x \in K \mid a_i \leq x \leq b_i\}.$$

Proof. Denote by 0 the minimal and by 1 the maximum element of K . Let $g: X \rightarrow K$ be defined by $g(x) = e_\alpha$ if $x \in J_\alpha$, then g is a monotone retraction. Let

(7) $x_0 = \sup \{e \in K \mid \text{for each } e' \leq e \text{ there exists an open cover}$

of $g^{-1}([0, e'])$ satisfying the conclusion of Lemma 2.1\},

then $x_0 \geq 0$. By (2) and (3) there exists an ε -chain $U_1, U_2, U_3, \dots, U_k$ in X covering $g^{-1}(x_0)$ such that

$$K \cap \bigcup_{j=2}^k U_j = \emptyset.$$

Since $g^{-1}(x_0) \subset \bigcup_{j=1}^k U_j$ and K is 0-dimensional there exists a closed and open set $H \subset K$ such that $g^{-1}(H) \subset \bigcup_{j=1}^k U_j$. Moreover, we can choose H such that

$$H \cap K = \{x \in K \mid a \leq x \leq b\}$$

for some a and b in K . If $a > 0$, define $x_1 = \sup \{x \in K \mid x < a\}$, then $x_1 \notin U_1$ and $x_1 < a$. By (7) there exists a cover U of $g^{-1}([0, x_1])$ satisfying the conclusions of the lemma (if $a = 0$, take $U = \emptyset$). Since $g^{-1}([0, x_1])$ is open in X we may assume that $\bigcup U \subset g^{-1}([0, x_1])$. Hence

$$U \cup \{U_j \cap g^{-1}(H) \mid j = 1, 2, \dots, k\}$$

is a cover of $g^{-1}([0, b])$ satisfying the conclusion of the lemma. It follows the definition of x_0 that $x_0 = b$.

If $x_0 = b = 1$, we are done, whence suppose $x_0 < 1$ and let $x_2 = \inf \{x \in K \mid x > x_0\}$. By repeating the argument above, replacing x_0 by x_2 , one can show that $g^{-1}([0, x_2])$ can be covered with a cover satisfying the conclusion of the lemma, contrary to (7), since $x_2 > x_0$.

We will call a cover U that satisfies the conclusion of Lemma 2.1 an ε -cover of X .

THEOREM 2.2. *Let X be a compact metric space and K a closed subset of X . Let $\{J_\alpha\}, \alpha \in A$, be the decomposition of X into components such that:*

(8) $J_\alpha \cap K = \{e\}$, where e is an end-point of J_α for each $\alpha \in A$,

(9) J_α is an arc-like continuum for each $\alpha \in A$. Then there exists an embedding $h: X \rightarrow I^2$ such that $h(K) = h(X) \cap l$, where $l = \{(x, y) \in I^2 \mid y = 0\}$.

Proof. Notice that by (8) K is 0-dimensional. By Lemma 2.1, there exists for each $\varepsilon > 0$ an ε -cover of X . Let U_1 be a $1/2$ -cover of X and $\eta > 0$ such that η is the minimum distance between two nonintersecting elements of U_1 . By induction we construct a sequence of covers U_1, U_2, \dots of X such that U_n refines U_{n-1} , U_n is a $(1/2)^n$ -cover, no sub-chain of less than nine links of U_n connects two non-intersecting elements of U_{n-1} .

Given a cover U of X , satisfying the conclusion of Lemma 2.1, we label the chains V_1, V_2, \dots, V_i of U such that $\inf \{x \mid x \in K \cap V_i\} < \inf \{x \mid x \in K \cap V_j\}$ if $i < j$, and the links of the chain $V_i = \{U(i, 1), U(i, 2), \dots, U(i, k(i))\}$ such that $K \cap V_i \subset U(i, 1)$. If U and U^* are both covers of X , satisfying the conclusion of Lemma 2.1, then we say that U follows the pattern $\{(a_1, b_1), (a_1, b_2), \dots, (a_1, b_{k(1)}), \dots, (a_i, b_{k(i)})\}$ in U^* if the j th link of the i th chain of U is contained in the b_j th link of the a_i th chain of U^* (i.e., $U(i, j) \subset U^*(a_i, b_j)$).

There exist in I^2 a sequence of open sets D_1, D_2, \dots such that D_n is a finite union of $(1/2)^n$ -chains whose elements are interiors of rectangles, and such that D_n follows a pattern in D_{n-1} that U_n follows in U_{n-1} , each element of D_{n-1} contains the closure of an element of D_n , while the closure of each element of D_n lies in an element of D_{n-1} and the first link of each chain of D_n intersects l in a non-degenerate interval, while the closure of all other elements of D_n are contained in $I^2 \setminus l$ ($n = 1, 2, \dots$).

The existence of the open sets D_n satisfying the above follows from an argument similar to one used by R. H. Bing (see [3], p. 654),

the only difference being that in each cover D_{n-1} we insert, in the next step, finitely many, instead of one, new chains and we require the first link of each chain of D_n to intersect l in a nondegenerate interval, while the closures of all other elements of D_n are contained in $I^n \setminus l$.

The latter facts can be established by dividing each chain of D_{n-1} into finitely many "strips" in each of which we insert, in the next step, a new chain in such a way that we always insert new links on a predescribed "side" of already chosen previous links.

It follows from Theorem 11 of [2] that X is homeomorphic with the continuum $Y = D_1^* \cap D_2^* \cap \dots$, where D_n^* denotes the union of the elements of D_n and moreover it follows from the choice of D_n that Y satisfies the conclusion of Theorem 2.2, and the proof is complete.

3. Fans locally connected at the vertex. A fan X has *property P*¹, if for each sequence of points $\{x_i\}$ in X ($i = 1, 2, \dots$) converging to the vertex v of X we have

$$(1) \quad Ls[v, x_i] = \{v\}.$$

THEOREM 3.1. *Let X be a fan with vertex v and*

$$(2) \quad X = \bigcup_{r \in R} \{J_r \mid J_r \cong [0, 1] \text{ for each } r \in R \text{ and } J_{r_1} \cap J_{r_2} = \{v\} \text{ if } r_1 \neq r_2 \in R\},$$

then the following are equivalent:

$$(3) \quad X \text{ has property } P,$$

$$(4) \quad \text{for each } \varepsilon > 0, \text{ there exists a connected open neighborhood } U \text{ of } v \text{ such that } \text{diam}(U) \leq \varepsilon \text{ and } \text{Bd}(U) \cap J_r \text{ is connected for every } r \in R,$$

$$(5) \quad X \text{ is locally connected at } v.$$

Proof. (3) \rightarrow (4). Let $\varepsilon > 0$ be given and let \leq be the weak-cut order of X with respect to v . Define $V = B(v, \varepsilon)$,

$$x(r) = \inf \{x \in X \mid x \in J_r \cap \text{Bd}(V)\} \text{ if } J_r \cap \text{Bd}(V) \neq \emptyset,$$

$$(6) \quad Q_r = \begin{cases} \{y \in J_r \mid y \geq x(r)\} & \text{if } J_r \cap \text{Bd}(V) \neq \emptyset \\ \emptyset & \text{otherwise} \end{cases}$$

and $Q = \bigcup_{r \in R} Q_r$. It follows that $v \notin \bar{Q}$, since if $\{v_i\}$ is a sequence in Q converging to v , then $v_i \geq x(r_i)$ for some $r_i \in R$, and hence $Ls[v, v_i] \cap \text{Bd}(V) \neq \emptyset$, contrary to (3).

Let $U = X \setminus \bar{Q}$, then U is an open neighborhood of v and $\text{diam}(U) \leq$

¹ It follows from the definition that property P is related to the notion of a Q -point or a P -point (cf. [1] and [7], respectively).

$\text{diam}(V) = \varepsilon$. We will show that U satisfies all conditions of (4). We claim that

(7) if $z \in U$ and $x < z$, then $x \in U$, or, equivalently, if $x \in \bar{Q}$ and $z \geq x$, then $z \in \bar{Q}$.

To this end, suppose that (7) is false. Hence $x \in \bar{Q}$, let $\{x_i\}$ be a sequence in Q converging to x . Then $x_i \geq x(r_i) \in \text{Bd}(V)$ for some $r_i \in R$ ($i = 1, 2, \dots$). We may assume that the sequence $\{x(r_i)\}$ converges to a point $x_0 \in J_{r_0} \cap \text{Bd}(V)$ for some $r_0 \in R$.

By ([9], p. 171), $Ls[x_i, x(r_i)]$ is a continuum and since $[x_i, x(r_i)] \subset Q$ ($i = 1, 2, \dots$) we have $Ls[x_i, x(r_i)] \subset \bar{Q} \subset X \setminus \{v\}$. Moreover, since X is hereditarily unicoherent, it follows that $[x, x_0] \subset Ls[x_i, x(r_i)] \subset \bar{Q} \subset X \setminus \{v\}$ and we consider two cases as follows:

Case 1. $z \in [x, x_0]$. Then $z \in \bar{Q}$.

Case 2. $z \notin [x, x_0]$. Then, since $z > x$, $z > \max\{x, x_0\}$ and consequently $z > x_0 \geq x(r_0)$. Hence $z \in Q$ by (6) and the definition of Q .

In both case we conclude that $z \in \bar{Q}$, contrary to the assumptions in (7) and the proof of (7) is complete. It follows from (7) that U is connected. In order to show that $J_r \cap \text{Bd}(U)$ is connected for each $r \in R$, we will show that if $x, y \in J_r \cap \text{Bd}(U)$, say $x < y$, and $z \in [x, y]$, then $z \in J_r \cap \text{Bd}(U)$.

Since $x \in J_r \cap \text{Bd}(U) = J_r \cap \bar{U} \cap \bar{Q}$ and $z > x$, it follows from (7) that $z \in \bar{Q}$. Moreover, since $y \in \bar{U}$, there exists a sequence $\{y_i\}$ in U converging to y . Since $Ls[v, y_i]$ is a continuum ([9], p. 171), containing both y and v and X is hereditarily unicoherent, it follows that $[v, y] \subset Ls[v, y_i]$. As $z \in [v, y]$, we may assume that there exists a sequence $\{z_i\}$, where $z_i \in [v, y_i]$, converging to z . By (7), $z_i \in U$ and whence $z \in \bar{U}$. Obviously $z \in J_r$ and we conclude $z \in J_r \cap \bar{U} \cap \bar{Q} = J_r \cap \text{Bd}(U)$.

(4) \rightarrow (5): Trivial.

(5) \rightarrow (3): Suppose X does not have property P . Let $\{x_i\}$ be a sequence of points in X converging to v such that $Ls[v, x_i] = K \neq \{v\}$.

Let $\varepsilon > 0$ be such that $\text{diam}(K) > 3\varepsilon$ and let U be a connected neighborhood of v such that $\text{diam}(U) < \varepsilon$. Then there exists an index $i > 0$ such that $x_i \in U$ and $[v, x_i] \cap [X \setminus B(v, 2\varepsilon)] \neq \emptyset$. But then \bar{U} and $[v, x_i]$ are two continua in X whose intersection is not connected, contradicting the fact that X is hereditarily unicoherent, and the proof is complete.

4. Decompositions of fans. We say that a space X is a $(q = c)$ -space if, in X , every quasi-component is connected. In other words, for $(q = c)$ -spaces the quasi-components and the components coincide. We will show that if a fan is locally connected at the vertex v of

X , then $X \setminus \{v\}$ is a $(q = c)$ -space.

THEOREM 4.1. *Let X be a fan which is locally connected at the vertex v of X and*

$$X = \bigcup_{r \in R} \{J_r \mid J_r \cong [0, 1] \text{ for each } r \in R \text{ and } J_{r_1} \cap J_{r_2} = \{v\} \\ \text{if } r_1 \neq r_2 \in R\}.$$

Then $X \setminus \{v\}$ is a $(q = c)$ -space and $\{J_r \setminus \{v\}\}$, $r \in R$, is the decomposition of $X \setminus \{v\}$ into quasi-components.

Proof. It is sufficient to show that if $r_0 \neq r_1 \in R$, then there exists a closed and open set $G \subset X \setminus \{v\}$ such that

$$(1) \quad J_{r_0} \setminus \{v\} \subset G \subset X \setminus J_{r_1}.$$

By Theorem 3.1 there exists for each $n (n = 1, 2, \dots)$ a neighborhood U_n of v such that $\text{diam}(U_n) < 1/n$, $\bar{U}_{n+1} \subset U_n$ and $\text{Bd}(U_n) \cap J_r$ is connected for each $r \in R$. We may assume that $J_{r_0} \cap \text{Bd}(U_1) \neq \emptyset \neq J_{r_1} \cap \text{Bd}(U_1)$. Let $R_n = \{r \in R \mid \text{Bd}(U_n) \cap J_r \neq \emptyset\} (n = 1, 2, \dots)$, then $R_n \subset R_{n+1}$ and $\bigcup_{n=1}^{\infty} R_n = R$.

Let Y be the space obtained from $\text{Bd}(U_1)$ by identifying all components of $\text{Bd}(U_1)$ to a point and let $f: \text{Bd}(U_1) \rightarrow Y$ be the natural projection. It follows ([9], p. 148) that $\dim Y = 0$. Since

$$f(J_{r_0} \cap \text{Bd}(U_1)) \neq f(J_{r_1} \cap \text{Bd}(U_1)),$$

there exists a closed and open set H_1^* in Y such that

$$f(J_{r_0} \cap \text{Bd}(U_1)) \subset H_1^* \subset Y \setminus f(J_{r_1} \cap \text{Bd}(U_1)).$$

Let $H_1 = f^{-1}(H_1^*)$, then H_1 is a closed and open set in $\text{Bd}(U_1)$. Define $A_1 = \{r \in R_1 \mid J_r \cap H_1 \neq \emptyset\}$ and $B_1 = \{r \in R_1 \mid J_r \cap H_1 = \emptyset\}$, then $A_1 \cap B_1 = \emptyset$ and $A_1 \cup B_1 = R_1$. Moreover, since H_1 is closed and open in $\text{Bd}(U_1)$, we have that

$$P_1 = \bigcup_{r \in A_1} \{J_r \setminus \{v\}\} \quad \text{and} \quad Q_1 = \bigcup_{r \in B_1} \{J_r \setminus \{v\}\}$$

are disjoint and closed subsets of $X \setminus \{v\}$.

By induction we will construct sets A_n and B_n such that

$$(2) \quad A_{n-1} \subset A_n, B_{n-1} \subset B_n, A_n \cap B_n = \emptyset \text{ and } A_n \cup B_n = R_n$$

and if $P_n = \bigcup_{r \in A_n} \{J_r\}$ and $Q_n = \bigcup_{r \in B_n} \{J_r\}$ then P_n and Q_n are disjoint and closed subsets of $X \setminus \{v\} (n = 1, 2, \dots)$.

Suppose A_{n-1} and B_{n-1} have been constructed. Since $P_{n-1} \cap \text{Bd}(U_n)$ and $Q_{n-1} \cap \text{Bd}(U_n)$ are disjoint closed subsets of $\text{Bd}(U_n)$ and

$J_r \cap \text{Bd}(U_n)$ is connected for each $r \in R$, it follows as above, replacing U_1 , $J_{r_0} \cap \text{Bd}(U_1)$ and $J_{r_1} \cap \text{Bd}(U_1)$ by U_n , $P_{n-1} \cap \text{Bd}(U_n)$ and $Q_{n-1} \cap \text{Bd}(U_n)$ respectively, that there exists a closed and open subset H_n of $\text{Bd}(U_n)$ such that

$$P_{n-1} \cap \text{Bd}(U_n) \subset H_n \subset \text{Bd}(U_n) \setminus Q_{n-1}.$$

Let $A_n = \{r \in R_n \mid J_r \cap H_n \neq \emptyset\}$ and $B_n = \{r \in R_n \mid J_r \cap H_n = \emptyset\}$, then A_n and B_n satisfy (2).

Let $A = \bigcup_{n=1}^{\infty} A_n$ and $B = \bigcup_{n=1}^{\infty} B_n$, then $A \cup B = R$ and $A \cap B = \emptyset$. Let $G = \bigcup_{r \in A} \{J_r \setminus \{v\}\}$ and $G_n = \bigcup_{r \in A_n} \{J_r \setminus \bar{U}_n\}$. Since G_n is open in X and $G = \bigcup_{n=1}^{\infty} G_n$, it follows that G is open in X . Similarly $X \setminus (G \cup \{v\}) = \bigcup_{r \in B} \{J_r \setminus \{v\}\}$ is open in X . Hence G is both open and closed in $X \setminus \{v\}$ and, since $r_0 \in A_1$ and $r_1 \in B_1$, (1) is proved.

5. Property P and embeddings in the plane. The main result of this section is Theorem 5.2 where we prove that if a fan is locally connected at its vertex, then it can be embedded in the plane. This result gives a solution to problem 1015 of [6].

Since every fan is hereditarily decomposable and hence 1-dimensional ([9], p. 206), we can consider every fan as a subspace of I^3 . We start with the following lemma.

LEMMA 5.1. *Let X be a fan, with vertex v and*

$$X = \bigcup_{r \in R} \{J_r \mid J_r \cong [0, 1] \text{ for each } r \in R \text{ and } J_{r_1} \cap J_{r_2} = \{v\} \\ \text{if } r_1 \neq r_2 \in R\}$$

such that $\{J_r \setminus \{v\}\}$, $r \in R$, is the decomposition of $X \setminus \{v\}$ into quasi-components, then there exists an embedding $f: X \setminus \{v\} \rightarrow C \times I^3$ such that each quasi-component of $X \setminus \{v\}$ is contained in $\{c\} \times I^3$ for some $c \in C$, and

$$(1) \quad \overline{f(X \setminus \{v\})} \setminus f(X \setminus \{v\}) \subset C \times \{v\},$$

where $C \subset [0, 1]$ denotes the Cantor ternary set.

Proof. We may assume that $X \subset I^3$. By ([9], p. 148), there exists a continuous function $g: X \setminus \{v\} \rightarrow C$ such that the quasi-components of $X \setminus \{v\}$ coincide with the point-inverses of g . Then the function $f: X \setminus \{v\} \rightarrow C \times I^3$ defined by $f(x) = (g(x), x)$ is an embedding. Only (1) remains to be shown. Let

$$(2) \quad (c_0, x_0) \in \overline{f(X \setminus \{v\})} \setminus f(X \setminus \{v\}),$$

and let $\{(c_i, x_i) \mid (i = 1, 2, \dots)\}$ be a sequence of points in $f(X \setminus \{v\})$ converging to (c_0, x_0) . We may assume that the sequence $\{x_i\}$ in X ,

where $x_i = f^{-1}((c_i, x_i))$, converges to a point $y \in X$. We consider two cases as follows:

Case 1. $y \neq v$. Then the sequence $\{f(x_i)\}$, where $f(x_i) = (c_i, x_i)$, converges to $f(y)$. Hence $f(y) = (c_0, x_0)$, contrary to (2).

Case 2. $y = v$. Then $x_0 = v$ and whence (1) holds.

These two cases complete the proof of the lemma.

THEOREM 5.2. *Let X be a fan which is locally connected at the vertex v of X , then X is embeddable in the plane.*

Proof. Let

$$X = \bigcup_{r \in R} \{J_r \mid J_r \cong [0, 1] \text{ for each } r \in R \text{ and } J_{r_1} \cap J_{r_2} = \{v\} \\ \text{if } r_1 \neq r_2 \in R\}.$$

It follows from 4.1 that $\{J_r \setminus \{v\}\}$, $r \in R$, is the decomposition of $X \setminus \{v\}$ into quasi-components. Hence by Lemma 5.1 there exists an embedding $f: X \setminus \{v\} \rightarrow C \times I^3$ such that each quasi-component of $X \setminus \{v\}$ is contained in $\{c\} \times I^3$ for some $c \in C$ and

$$\overline{f(X \setminus \{v\})} \setminus f(X \setminus \{v\}) \subset C \times \{v\}.$$

It follows that $\overline{f(X \setminus \{v\})}$ satisfies all conditions of Theorem 2.2, where $K = \overline{f(X \setminus \{v\})} \cap (C \times \{v\})$. Hence there exists an embedding $h: \overline{f(X \setminus \{v\})} \rightarrow I^2$ such that $h(K) = h(\overline{f(X \setminus \{v\})}) \cap l$, where $l = \{(x, y) \in I^2 \mid y = 0\}$. Let $\pi: I^2 \rightarrow I^2/l$ be the natural projection. It follows (see [9], p. 533) that $I^2 \cong I^2/l$ and whence the mapping $g: X \rightarrow I^2/l$ defined by

$$g(x) = \begin{cases} \pi \circ h \circ f(x) & \text{if } x \neq v, \\ \pi(l) & \text{if } x = v \end{cases}$$

is the required embedding.

REMARK. J. J. Charatonik and Z. Rudy constructed a fan X which is locally connected at its vertex (see [6], p. 215). They conjectured that this fan is not embeddable in the plane. The above theorem disproves their conjecture and gives a solution to problem 1015 of [6].

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Patrick Robert Ahern, <i>On a theorem of Hayman concerning the derivative of a function of bounded characteristic</i>	297
Walter Allegretto, <i>Finiteness of lower spectra of a class of higher order elliptic operators</i>	303
Leonard Asimow, <i>Superharmonic interpolation in subspaces of $C_c(X)$</i>	311
Steven F. Bellenot, <i>An anti-open mapping theorem for Fréchet spaces</i>	325
B. J. Day, <i>Locale geometry</i>	333
John Erik Fornæss and Steven Krantz, <i>Continuously varying peaking functions</i>	341
Joseph Leonide Gerver, <i>Long walks in the plane with few collinear points</i>	349
Joseph Leonide Gerver and Lawrence Thom Ramsey, <i>On certain sequences of lattice points</i>	357
John R. Graef, Yuichi Kitamura, Takaši Kusano, Hiroshi Onose and Paul Winton Spikes, <i>On the nonoscillation of perturbed functional-differential equations</i>	365
James A. Huckaba and James M. Keller, <i>Annihilation of ideals in commutative rings</i>	375
Anzelm Iwanik, <i>Norm attaining operators on Lebesgue spaces</i>	381
Surjit Singh Khurana, <i>Pointwise compactness and measurability</i>	387
Charles Philip Lanski, <i>Commutation with skew elements in rings with involution</i>	393
Hugh Bardeen Maynard, <i>A Radon-Nikodým theorem for finitely additive bounded measures</i>	401
Kevin Mor McCrimmon, <i>Peirce ideals in Jordan triple systems</i>	415
Sam Bernard Nadler, Jr., Joseph E. Quinn and N. Stavrakas, <i>Hyperspaces of compact convex sets</i>	441
Ken Nakamura, <i>An explicit formula for the fundamental units of a real pure sextic number field and its Galois closure</i>	463
Vassili Nestoridis, <i>Inner functions invariant connected components</i>	473
Vladimir I. Olikier, <i>On compact submanifolds with nondegenerate parallel normal vector fields</i>	481
Lex Gerard Oversteegen, <i>Fans and embeddings in the plane</i>	495
Shlomo Reisner, <i>On Banach spaces having the property G.L.</i>	505
Gideon Schechtman, <i>A tree-like Tsirelson space</i>	523
Helga Schirmer, <i>Fix-finite homotopies</i>	531
Jeffrey D. Vaaler, <i>A geometric inequality with applications to linear forms</i>	543
William Jennings Wickless, <i>T as an \mathcal{Q} submodule of G</i>	555
Kenneth S. Williams, <i>The class number of $Q(\sqrt{-p})$ modulo 4, for $p \equiv 3 \pmod{4}$ a prime</i>	565
James Chin-Sze Wong, <i>On topological analogues of left thick subsets in semigroups</i>	571