DIMENSION ON BOUNDARIES OF $\varepsilon$-SPHERES

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The purpose of this paper is to make somewhat more accessible the topological dimension-theoretic properties of metric spaces. We shall show that any metric for a space can be replaced by a topologically equivalent metric which has the following property: the boundary of any $\varepsilon$-sphere meets each of a specified countable collection of closed, finite-dimensional subsets in a set of lower dimension. An additional property of the new metric is that for any fixed $\varepsilon$, the collection of all $\varepsilon$-spheres is closure-preserving.

In the case of a separable metric space, the result can be sharpened to produce a totally bounded metric with the above properties, and in this case we obtain for each fixed $\varepsilon$ at most finitely many distinct $\varepsilon$-spheres.

Our dimension function, denoted by $\dim$, will be the covering dimension of Lebesgue. All spaces throughout this paper will be metric, and under this condition the Lebesgue dimension coincides with the inductive dimension in the large of Menger and Urysohn [6]. Now let us consider a space together with countably many closed, finite-dimensional subsets $X_1, X_2, \ldots$; these subsets need not cover $X$ ($X$ itself may not even be finite-dimensional). It is immediate from the Menger-Urysohn definition of dimension that for any point $p \in X$ and any fixed positive integer $k$, there exists a fundamental system of neighborhoods of $p$ for which the boundaries meet $X_k$ in a set of dimension lower than that of $X_k$. There is no reason why any of these neighborhoods should be $\varepsilon$-spheres under the given metric; J. Nagata, however, has shown [8] that if any $X_k = X$, then an equivalent metric can be defined on $X$ such that the boundary of any $\varepsilon$-sphere (about any point) has dimension lower than that of $X$. We shall prove that this condition can be dispensed with and that an equivalent metric can be introduced on $X$ in such a way that the boundary of any $\varepsilon$-sphere meets each of the $X_k$ in a set of lower dimension:

**Theorem 1.** For each $k = 1, 2, \ldots$ let $X_k$ be a nonvoid closed subset of $X$ such that $\dim X_k = n_k < \infty$. Then there exists an equivalent metric $\rho$ for $X$ such that for any $\varepsilon > 0$, any $x \in X$, and any positive integer $k$,

$$\dim [X_k \cap \text{Bdry } S(x, \varepsilon)] \leq n_k - 1.$$  

We shall define this metric by constructing a uniformity with
certain desirable properties. To construct the uniformity we shall need several lemmas, and we make the following definitions to clarify the terminology.

**Definition.** Let \( \mathcal{G} \) be a collection of subsets of \( X \), and \( p \in X \).

(i) **Local order**, \( \mathcal{G} \leq n \) if and only if there exists a neighborhood of \( p \) which meets at most \( n \) members of \( \mathcal{G} \).

(ii) **Local order**, \( \mathcal{G} \leq n \) if and only if for all \( x \in X \), local order \( x \)

(iii) \( \mathcal{G} = \{ G : G \in \mathcal{G} \} \).

**Lemma 1.1.** Let \( F \) be a closed subset of \( (X,d) \), \( \dim F \leq n \), and \( \mathcal{U} = \{ U_\alpha : \alpha \in A \} \) a collection of open subsets of \( X \) which covers \( F \). Then there exists a collection \( \mathcal{B} = \{ V_\alpha : \alpha \in A \} \) of open subsets of \( X \) which covers \( F \), refines \( \mathcal{U} \) one-to-one, and such that local order \( \mathcal{B} \leq n + 1 \).

**Proof.** Let \( \mathcal{G} = \{ G_\alpha : \alpha \in A \} \) be a locally finite open cover of \( F \) such that \( G_\alpha \subseteq U_\alpha \) for all \( \alpha \in A \). Since \( \dim F \leq n \), there exists a locally finite closed cover \( \mathcal{F} = \{ F_\alpha : \alpha \in A \} \) of \( F \) such that order \( \mathcal{F} \leq n + 1 \) and \( F_\alpha \subseteq G_\alpha \) for all \( \alpha \in A \) ([1], [5]). Then, by [5, Lemma in § 3 and Theorem 1.3] there exists a locally finite collection \( \mathcal{B} = \{ V_\alpha : \alpha \in A \} \) of open subsets of \( X \) such that order \( \mathcal{B} = \) order \( \mathcal{F} \) and for each \( \alpha \in A \), \( F_\alpha \subseteq V_\alpha \subseteq \overline{V_\alpha} \subseteq U_\alpha \). For each \( x \in X \) the set

\[
X - \bigcup \{ \overline{V_\alpha} : x \in \overline{V_\alpha} \}
\]

is a neighborhood of \( x \) which meets at most \( n + 1 \) members of \( \mathcal{B} \), so \( \mathcal{B} \) is the desired collection and the Lemma is proved.

**Lemma 1.2.** Let \( X_1, \cdots, X_k \) be closed subsets of \( X \) such that \( \dim X_i = n_i < \infty \) for all \( i = 1, \cdots, k \), and let \( \mathcal{U} \) be an open cover of \( X \). Then there exists a locally finite open cover \( \mathcal{B} \) of \( X \) satisfying

(i) \( \mathcal{B} \leq \mathcal{U} \)

(ii) for all \( i = 1, \cdots, k \) and all \( x \in X_i \), local order \( x \)

\( \mathcal{B} \leq n_i + 1 \).

**Proof.** We shall first prove the lemma for the case \( n_1 = \cdots = n_k \).

By Lemma 1.1 we obtain an open refinement \( \mathcal{B}_1 \) of \( \mathcal{U} \) covering \( X_1 \) such that local order \( \mathcal{B}_1 \leq n_1 + 1 \); then the normality of \( X \) gives us an open set \( W_1 \) such that \( X_1 \subseteq W_1 \subseteq \overline{W_1} \subseteq \bigcup \mathcal{B}_1 \). If we define \( \mathcal{U}_2 = \mathcal{U} \cap \{ X - \overline{W_1} \} \), we see that \( \mathcal{B}_1 \cup \mathcal{U}_2 \) is an open cover of \( X_1 \cup X_2 \), and we can hence apply Lemma 1.1 again to obtain an open one-to-one refinement \( \mathcal{B}_2 \) which covers \( X_1 \cup X_2 \) and such that local order \( \mathcal{B}_2 \leq n_2 + 1 \). Therefore, we can apply Lemma 1.1 to obtain an open one-to-one refinement \( \mathcal{B}_3 \) which covers \( X_1 \cup X_3 \) and such that local order \( \mathcal{B}_3 \leq n_3 + 1 \). The author is indebted to the referee for shortening the proof of this lemma.
Continuing in this manner, we finally define the open set \( W_k \) such that \( \bigcup_{i=1}^k X_i \subset W_k \subset \bar{W}_k \subset \bigcup B_k \), and the open collection \( U_{k+1} = U \land \{ X - W_i \} \).

Now let \( B \) be a locally finite open one-to-one refinement of \( B_k \cup U_{k+1} \); we assert that \( B \) is the desired cover. The cover \( B \) satisfies (i), as

\[
\mathcal{B} < \mathcal{B}_k \cup U_{k+1} < (\mathcal{B}_{k-1} \cup U_k) \cup U_{k+1} < \mathcal{B}_{k-2} \cup \left( \bigcup_{i=k-1}^{k+1} U_i \right) < \cdots < \mathcal{B}_1 \cup \left( \bigcup_{i=2}^{k+1} U_i \right) < U.
\]

For condition (ii), let \( x \in X_i \) and let \( N(x, i) \) be an open neighborhood of \( x \) meeting at most \( n_i + 1 \) sets of \( B_i \). Then we define the open neighborhood \( N(x) = N(x, i) \cap (\bigcap_{j=i}^k W_j) \); we need only show that \( N(x) \) meets at most \( n_i + 1 \) sets of \( B \).

First we show that \( N(x) \) meets at most \( n_i + 1 \) sets of \( B_{i+1} \). Suppose \( V_a \cap N(x) \neq \emptyset \) for some \( V_a \in B_{i+1} \); then \( V_a \) is a subset of the corresponding \( U_a \in \mathcal{B}_i \cup U_{i+1} \). As \( N(x) \subset W_i \) and \( (\bigcup U_{i+1}) \cap W_i = \emptyset \), we know \( U_a \in \mathcal{B}_i \). But \( N(x) \cap U_a \neq \emptyset \) for at most \( n_i + 1 \) sets \( U_a \in \mathcal{B}_i \) (as \( N(x) \subset N(x, i) \)), and hence \( N(x) \cap V_a \neq \emptyset \) for at most the corresponding \( n_i + 1 \) sets \( V_a \in \mathcal{B}_{i+1} \) (as \( \mathcal{B}_{i+1} \) refines \( \mathcal{B}_i \cup U_{i+1} \) one-to-one). This argument can be repeated to show that \( N(x) \) meets at most \( n_i + 1 \) sets of \( \mathcal{B}_{i+2}, \ldots, \mathcal{B}_k \), and finally \( \mathcal{B} \), and we see that \( \mathcal{B} \) satisfies condition (ii).

To prove the lemma in its general form, we rearrange the \( X_i \) in such a way as to make their dimensions increase monotonely. Then the above proof will show that the conditions are satisfied, and the lemma is proved (as neither condition is concerned with the order in which the \( X_i \) are arranged).

**Lemma 1.3.** For each \( i = 1, \ldots, k \), let \( X_i \) be a closed subset of \( X \), and let \( \mathcal{U} \) be a locally finite open cover of \( X \) such that for all \( i \leq k \) and each \( x \in X_i \), local order \( \mathcal{U} \leq m_i \). Then there exists an open cover \( \mathcal{B} \) of \( X \) such that

(i) \( \mathcal{B}^{**} \subset \mathcal{U} \),
(ii) for each \( i = 1, \ldots, k \) and every \( x \in X_i \), \( S^i(x, \mathcal{B}) \) meets at most \( m_i \) sets of \( \mathcal{U} \), and
(iii) for every \( x \in X \), \( S^i(x, \mathcal{B}) \) meets only a finite number of sets of \( \mathcal{U} \).

**Proof.** For each \( i = 1, \ldots, k \) and every \( x \in X_i \) we define \( N(x, i) \) to be an open neighborhood of \( x \) meeting at most \( m_i \) sets of \( \mathcal{U} \). We then define \( \mathcal{G}_i = \{ X - X_i \} \cup \{ N(x, i) : x \in X_i \} \), and note that \( \mathcal{G}_i \) is an open cover of \( X \), as \( X_i \) is closed. Now for any \( x \in X \) we define an-
other set \( N(x) \) to be a neighborhood of \( x \) meeting only a finite number of members of \( U \), and define \( G_{k+1} = \{ N(x): x \in X \} \). Now we define \( G = (\bigwedge_{i=1}^{k+1} G_i) \cap U \). The collection \( G \) is an open cover of \( X \), so we can define \( B \) to be an open cover of \( X \) such that \( B_{**} \subset G \) (\( B \) exists by the full normality of \( X \)). We shall now prove that \( B \) is the desired cover.

Condition (i) is clear, as \( B_{***} \subset G \subset U \). For (ii) we let \( i \leq k \) and let \( x \in X \); then there exists some \( V \in B \) which contains \( x \), as \( B \) covers \( X \), and there exists a set \( V_{***} \in B_{***} \) such that

\[
B_{**} = S(S(S(V, B), B^*), B^{**}) \subset S(S(S(x, B), B^*), B^{**}) \subset S(S(x, B), B^{**}) \subset S(x, B).
\]

Since \( B_{***} \subset G \) we know there exists a set \( G \in G \) such that \( V_{***} \subset G \). As \( G \subset G \), and \( G \cap X_i \neq \emptyset \), there exists a point \( y \in X_i \) such that \( G \subset N(y, i) \). Thus \( S(x, B) \subset V_{***} \subset G \subset N(y, i) \), so \( S(x, B) \) meets at most \( m_i \) elements of \( U \).

In the same manner we see that, for any \( x \in X \), there exist \( W_{***} \in B_{***} \), \( H \in G \), and \( N(z) \) such that \( S(z, B) \subset W_{***} \subset H \subset N(z) \), so \( S(z, B) \) meets only finitely many elements of \( U \).

**Proof of Theorem 1.** We shall use Lemmas 1.2 and 1.3 to develop a sequence \( \{ U_i: i = 0, 1, 2, \cdots \} \) of open covers of \( X \) with special properties. First we define \( U_0 = \{ X \} \). Now set \( G_i = \{ S(x, 1/4): x \in X \} \); by Lemma 1.2 there exists a locally finite open cover \( U_i \) of \( X \) satisfying

1. \( U_i \subset G_i \)
2. for all \( x \in X \), local order \( U_i \leq n_i + 1 \)
3. mesh \( U_i \leq 1/2 \), and
4. \( U_i^{**} \subset U_i \).

Therefore an application of Lemma 1.3 yields an open cover \( B_2 \) of \( X \) such that

1. \( B_2^{**} \subset U_i \),
2. for all \( x \in X \), \( S(x, B) \) meets at most \( n_i + 1 \) members of \( U_i \), and
3. for all \( x \in X \), \( S(x, B) \) meets only finitely many members of \( U_i \).

Now set \( G_2 = B_2 \cap \{ S(x, 1/8): x \in X \} \), and apply Lemma 1.2 to obtain a locally finite open cover \( U_2 \) of \( X \) satisfying

1. \( U_2 \subset G_2 \), and
2. for \( j = 1, 2 \), all \( x \in X \), local order \( U_2 \leq n_j + 1 \). We note also that \( U_2 \) satisfies
3. mesh \( U_2 \leq 1/4 \),
4. \( U_2^{**} \subset U_2 \),
5. for all \( x \in X \), \( S(x, U_2) \) meets at most \( n_i + 1 \) members of \( U_i \), and
(6') for all \( x \in X, S^0(x, \mathcal{U}_n) \) meets only a finite number of members of \( \mathcal{U}_n \).

By alternating applications of Lemma 1.2 and Lemma 1.3, the same method can be used to construct \( \mathcal{U}_3, \mathcal{U}_4, \ldots \) with properties analogous to (1')-(6') above. This procedure will yield a sequence \( \{ \mathcal{U}_i : i = 0, 1, 2, \ldots \} \) of open covers of \( X \) satisfying the following four conditions:

1. \( \{X\} = \mathcal{U}_0 > \mathcal{U}_1 > \mathcal{U}_2 > \cdots \),
2. for \( i = 1, 2, \ldots \), mesh \( \mathcal{U}_i \leq 1/2^i \),
3. for \( j = 1, 2, \ldots \), all \( x \in X_j \), all \( i \geq j \), \( S^0(x, \mathcal{U}_{i+j}) \) meets at most \( n_j + 1 \) members of \( \mathcal{U}_i \), and
4. for \( i = 1, 2, \ldots \), all \( x \in X, S^0(x, \mathcal{U}_{i+1}) \) meets only finitely many members of \( \mathcal{U}_i \).

We shall use these covers to define certain open subsets of \( X \), and the new metric will be defined in terms of collections of these subsets. For any finite set \( 0 < m_1 < \cdots < m_p \) of integers and any open subset \( U \) of \( X \) we define inductively an open set \( S_{m_2 \cdots m_p}(U) \) by

\[
S_{m_2 \cdots m_p}(U) = U \quad \text{for} \ p = 1, \text{ and } \\
S_{m_2 \cdots m_p}(U) = S^0(S_{m_2 \cdots m_{p-1}}(U), \mathcal{U}_{m_p}) \quad \text{for} \ p > 1.
\]

Next we define open covers of \( X \) by

\[ \mathcal{O}_{m_1} = \mathcal{U}_{m_1}, \text{ and } \]
\[ \mathcal{O}_{m_1 \cdots m_p} = \{ S_{m_2 \cdots m_p}(U) : U \in \mathcal{U}_{m_1} \} \quad \text{for} \ p > 1. \]

Now we define a nonnegatively valued function \( \rho \) on \( X \times X \) by

\[
\rho(x, y) = \inf \{ 1/2^m_1 + \cdots + 1/2^m_p : y \in S(x, \mathcal{O}_{m_1 \cdots m_p}) \}. 
\]

J. Nagata has shown [7] that if a function \( \gamma \) is defined in this way from a sequence of covers which possesses properties (1) and (2), then \( \gamma \) is a metric on \( X \) equivalent to the given metric.

Now for any sequence \( 0 \leq m_1 < m_2 < \cdots \) of integers and any open subset \( U \) of \( X \), we define the open set

\[
S_{m_2 \cdots m_3}(U) = \bigcup_{i=1}^\infty S_{m_2 \cdots m_i}(U)
\]

and the open cover

\[ \mathcal{O}_{m_1 m_2 \cdots} = \{ S_{m_2 \cdots m_3}(U) : U \in \mathcal{U}_{m_1} \}. \]

Now let \( \varepsilon \) be such that \( 0 < \varepsilon \leq 1 \). Then \( \varepsilon \) has a unique nonterminating expansion

\[
(1.1) \quad \varepsilon = 1/2^m_1 + 1/2^m_2 + \cdots, \quad \text{where} \ 1 \leq m_1 < m_2 < \cdots,
\]
and we can prove that for any \( x \in X \),

\[
S(x, \varepsilon) = S(x, \varnothing_{m_1m_2\ldots}) ,
\]

in the same manner used by Nagata [8] (where the \( \varepsilon \)-sphere is assumed to be with respect to \( \rho \)).

We shall use (1.2) to prove that for any \( x \in X \) and any

\[
k = 1, 2, \ldots, \dim [X_k \cap \text{Bdry } S(x, \varepsilon)] \leq n_k - 1 .
\]

Before doing this, we note that for any finite set \( 1 \leq m_1 < \cdots < m_p \) of integers and any open subset \( U \) of \( X \),

\[
S^*(S_{m_2\ldots m_p-1}(U), \varnothing_{m_p}) \subset S^*(U, \varnothing_{m_1+1}) ;
\]

this relation is due to Nagata [8]. Hence it is immediate that for any sequence of integers \( 1 \leq m_1 < m_2 < \cdots \), we have

\[
S_{m_2m_3\ldots}(U) \subset S^*(U, \varnothing_{m_1+1}) ,
\]

and therefore

\[
(1.3) \quad \overline{S_{m_2m_3\ldots}(U)} \subset S^*(U, \varnothing_{m_1+1}) .
\]

We are now in a position to prove that

\[
(1.4) \quad \varnothing_{m_1m_2\ldots} \text{ is locally finite, for } 1 \leq m_1 < m_2 < \cdots .
\]

We can show that if \( x \in X \) and \( x \in U' \in \varnothing_{m_1+1} \), then \( U' \) is the desired neighborhood of \( x \). For if \( U' \) meets \( \overline{S_{m_2m_3\ldots}(U)} \) for \( U \in \varnothing_{m_1} \), then \( U' \) meets \( S^*(U, \varnothing_{m_1+1}) \) by (1.3); hence \( U \) meets \( S^*(x, \varnothing_{m_1+1}) \) (as \( U' \in \varnothing_{m_1+1} \)). By condition (4) this can occur for at most finitely many \( U \in \varnothing_{m_1} \), so \( U' \) meets at most finitely many members of \( \varnothing_{m_1m_2\ldots} \).

By using condition (3) instead of (4) in the above proof, we see also that

\[
(1.5) \quad \text{order}_y \varnothing_{m_1m_2\ldots} \leq n_k + 1 \quad \text{for } k \leq m_1 < m_2 < \cdots \quad \text{and } y \in X_k .
\]

We shall use this fact to prove that for \( x \in X, \varepsilon \) as in (1.1), \( i \geq k \), and \( y \in [X_k \cap \text{Bdry } S(x, \varepsilon)] \), then \( \text{order}_y \varnothing_{m_i} \leq n_k \). For suppose there existed distinct members \( U_1, \ldots, U_{n_k+1} \) of \( \varnothing_{m_i} \) containing \( y \). Now

\[
y \in \overline{S(x, \varepsilon)} = \overline{S(x, \varnothing_{m_1m_2\ldots})} = \bigcup \{ S_{m_2m_3\ldots}(U) : U \in \varnothing_{m_1}, x \in S_{m_2m_3\ldots}(U) \} = \bigcup \{ S_{m_2m_3\ldots}(U) : U \in \varnothing_{m_1}, x \in S_{m_2m_3\ldots}(U) \}
\]

by (1.4), so there exists a set \( U' \in \varnothing_{m_1} \) such that
y ∈ \overline{S_{m_{i+1}m_{i+2}...}(U')} = \overline{S_{m_{i+1}m_{i+2}...(S_{m_{i}}...(U'))}}
= \overline{S_{m_{i+1}m_{i+2}...}(U \cup \{ U \in \mathcal{U}_{m_{i}} : U \subset S_{m_{2}...m_{i}}(U') \})}
= \bigcup \{ S_{m_{i+1}m_{i+2}...}(U) : U \in \mathcal{U}_{m_{i}}, U \subset S_{m_{2}...m_{i}}(U') \}
= \bigcup \{ \overline{S_{m_{i+1}m_{i+2}...}(U)} : U \in \mathcal{U}_{m_{i}}, U \subset S_{m_{2}...m_{i}}(U') \},

again by (1.4). Hence there exists a set \( U \in \mathcal{U}_{m_{i}} \) such that \( y \in \overline{S_{m_{i+1}m_{i+2}...}(U)} \) and such that \( U \subset S_{m_{2}...m_{i}}(U') \subset S(x, \varepsilon) \); this set \( U \) cannot be the same as any one of \( U_{1}, \cdots, U_{n_{k}+1} \), as each of the latter contains the boundary point \( y \) of \( S(x, \varepsilon) \). But
\[ y \in S_{m_{i+1}m_{i+2}...(U_{j})} \quad \text{for all } j = 1, \cdots, n_{k} + 1, \]
and by the above we know that \( y \in \overline{S_{m_{i+1}m_{i+2}...}(U)} \), so
\[ \text{order}_{y} \mathcal{S}_{m_{i+1}m_{i+2}...} \geq n_{k} + 2, \]
which contradicts (1.5).

To complete the proof of the theorem, we first note that the condition is trivially satisfied by \( \varepsilon > 1 \), so we may assume \( 0 < \varepsilon \leq 1 \) and hence \( \varepsilon \) may be written as in (1.1). For any \( x \in X \) and \( k = 1, 2, \cdots \), we define \( \mathcal{U}_{m_{i}} = U_{m_{i}} \cap \{ X_{k} \cap \text{Bdry } S(x, \varepsilon) \} \) for all \( i \geq k \). Then \( \{ \mathcal{U}_{m_{i}} : i = k, k+1, \cdots \} \) is a sequence of relatively open covers of
\[ X_{k} \cap \text{Bdry } S(x, \varepsilon) \]
of order \( \leq n_{k} \) with mesh \( \to 0 \) as \( i \to \infty \) and such that for all \( i \geq k \), \( \mathcal{U}_{m_{i+1}} \subset \mathcal{U}_{m_{i}} \). Thus by a Theorem of C. H. Dowker and W. Hurewicz [2] we conclude that \( \text{dim } [ X_{k} \cap \text{Bdry } S(x, \varepsilon) ] \leq n_{k} - 1 \).

**Corollary 2.** If \( \rho \) is the metric for \( X \) constructed in the proof of Theorem 1, then for each \( \varepsilon > 0 \) the collection \( \{ S(x, \varepsilon) : x \in X \} \) is closure-preserving.

**Proof.** As in Theorem 1 we note that the case \( \varepsilon > 1 \) is trivial, as \( S(x, \varepsilon) = X \) for every \( x \in X \). For \( 0 < \varepsilon \leq 1 \) we can write \( \varepsilon \) as in (1.1), so for any subset \( A \) of \( X \) we have
\[ \bigcup \{ S(x, \varepsilon) : x \in A \} \]
\[ = \bigcup \{ \overline{S_{m_{2}m_{3}...}(U)} : U \in \mathcal{U}_{m_{1}}, x \in S_{m_{2}m_{3}...}(U) \} : x \in A \}
\[ = \bigcup \{ S_{m_{2}m_{3}...}(U) : U \in \mathcal{U}_{m_{1}}, A \cap S_{m_{2}m_{3}...}(U) \neq \emptyset \}
\[ = \bigcup \{ \overline{S_{m_{2}m_{3}...}(U)} : U \in \mathcal{U}_{m_{1}}, A \cap S_{m_{2}m_{3}...}(U) \neq \emptyset \}
\[ = \bigcup \{ S_{m_{2}m_{3}...}(U) : U \in \mathcal{U}_{m_{1}}, x \in S_{m_{2}m_{3}...}(U) \} : x \in A \}
\[ = \bigcup \{ S(x, \varepsilon) : x \in A \}
\]
by (1.4), which completes the proof of the corollary.
When we restrict our attention to the separable metric case, we would hope that the new metric would be totally bounded in addition to satisfying the conditions of Theorem 1 and Corollary 2. This is indeed the case if we use finite covers throughout.

**Theorem 3.** Let \((X, d)\) be separable and for each \(k = 1, 2, \ldots\) let \(X_k\) be a nonvoid closed subset of \(X\) such that \(\dim X_k = n_k < \infty\). Then there exists a totally bounded metric \(\rho\) for \(X\), equivalent to \(d\), such that for any \(\varepsilon > 0\), any \(x \in X\), and any positive integer \(k\), \(\dim [X_k \cap \text{Bdry } S(x \in \varepsilon)] \leq n_k - 1\).

We shall need to restate Lemmas 1.1-1.3 in terms of finite covers before we can prove Theorem 3. In each case only a minor adjustment is required.

**Lemma 3.1.** Let \(F\) be a closed subset of \((X, d)\), \(\dim F \leq n\), and \(\mathcal{U}\) a finite open cover of \(F\). Then there exists a finite open one-to-one refinement \(\mathcal{B}\) of \(\mathcal{U}\), covering \(F\), and such that local order \(\mathcal{B} \leq n + 1\).

*Proof.* The proof of Lemma 1.1 can be used without modification, as a one-to-one refinement of a finite cover must itself be finite.

**Lemma 3.2.** Let \(X_1, \ldots, X_k\) be closed subsets of \(X\) such that \(\dim X_i = n_i < \infty\) for all \(i = 1, \ldots, k\), and let \(\mathcal{U}\) be a finite open cover of \(X\). Then there exists a finite open cover \(\mathcal{B}\) of \(X\) satisfying

1. \(\mathcal{B} < \mathcal{U}\), and
2. for all \(i = 1, \ldots, k\) and all \(x \in X_i\), local order \(x\) \(\mathcal{B} \leq n_i + 1\).

*Proof.* We use the proof of Lemma 1.2, substituting Lemma 3.1 for Lemma 1.1. Then \(\mathcal{B}_i\) and \(\mathcal{U}_2\) are finite, so \(\mathcal{B}_i \cup \mathcal{U}_2\) and hence \(\mathcal{B}_2\) are finite. Similarly, \(\mathcal{B}_k \cap \mathcal{U}_{k+1}\) is finite, so the one-to-one refinement \(\mathcal{B}\) is itself finite.

**Lemma 3.3.** For each \(i = 1, \ldots, k\), let \(X_i\) be a closed subset of \(X\), and let \(\mathcal{U}\) be a finite open cover of \(X\) such that for all \(i \leq k\) and each \(x \in X_i\), local order \(x\) \(\mathcal{U} \leq m_i\). Then there exists a finite open cover \(\mathcal{B}\) of \(X\) such that

1. \(\mathcal{B}^* < \mathcal{U}\), and
2. for each \(i = 1, \ldots, k\) and every \(x \in X_i\), \(S^*(x, \mathcal{B})\) meets at most \(m_i\) sets of \(\mathcal{U}\).

*Proof.* For each \(x \in X\) we define the set
\[ N(x) = \bigcap \{ U \in \mathcal{U} : x \in U \} - \bigcup \{ \bar{U} \in \bar{\mathcal{U}} : x \notin \bar{U} \} \]

for all \( i \leq k \), \( N(x) \) is a neighborhood of \( x \) which meets at most \( m_i \) members of \( \mathcal{U} \). Furthermore, there are only finitely many distinct \( N(x) \), as there are only finitely many ways in which elements of the finite set \( \mathcal{U} \) can be combined, so for each \( i = 1, \cdots, k \), the family

\[ \mathcal{G}_i = \{ X - X_i \} \cup \{ N(x) : x \in X_i \} \]

is a finite open cover of \( X \) (assuming we count each distinct element only once). Hence \( \mathcal{G} = \left( \bigwedge_{i=1}^{k} \mathcal{G}_i \right) \cap \mathcal{U} \) is a finite open cover of \( X \).

To find a finite open cover \( \mathcal{B} \) such that \( \mathcal{B}^{**} \subset \mathcal{G} \), it suffices to establish that any finite open cover has a finite \( \mathcal{A} \)-refinement. This follows from a proof of K. Morita [5, Th. 1.2], in which a \( \mathcal{A} \)-refinement is constructed from intersections of binary covers; if the original cover were finite, then the total number of possible intersections would be finite, so the resulting \( \mathcal{A} \)-refinement would have to be a finite cover.

The proof that \( \mathcal{B} \) satisfies (i) and (ii) is exactly the same as in Lemma 1.3, and the lemma is proved.

Proof of Theorem 3. We shall closely follow the proof of Theorem 1, using Lemmas 3.2 and 3.3 (instead of 1.2 and 1.3) to construct a sequence \( \{ \mathcal{U}_i : i = 0, 1, 2, \cdots \} \) of finite open covers which satisfies conditions (1)--(4). This can be done exactly as in Theorem 1 if we know that for each positive integer \( i \), there exists a finite cover of \( X \) of \( 1/2^i \)-spheres. Although this may not be possible with respect to the given metric \( d \), the fact that \( X \) is separable guarantees the existence of a totally bounded metric \( d' \) for \( X \) which is equivalent to \( d \) [3, Th. V4]. Therefore we can proceed as in Theorem 1 to construct \( \{ \mathcal{U}_i : i = 0, 1, 2, \cdots \} \) and then to define the metric \( \rho \) which is equivalent to \( d' \) and hence to \( d \). The proof that the boundaries of the \( \varepsilon \)-spheres (with respect to \( \rho \)) meet the \( X_k \) in sets of lower dimension is exactly the same as in Theorem 1, so to prove Theorem 3 it suffices to show that \( \rho \) is totally bounded.

We need only consider \( \varepsilon \) such that \( 0 < \varepsilon \leq 1 \), which we can write as in (1.1). But \( \{ S(x, \varepsilon) : x \in X \} = \{ S(x, \mathcal{G}_1, \mathcal{G}_2, \cdots) : x \in X \} \) by (1.2), and \( \mathcal{G}_1, \mathcal{G}_2, \cdots \) is finite as \( \mathcal{U}_1 \) is finite, so there are only finitely many distinct sets of the form \( S(x, \mathcal{G}_1, \mathcal{G}_2, \cdots) = S(x, \varepsilon) \). This proves Theorem 3, and also proves the following analogue of Corollary 2:

Corollary 4. If \( \rho \) is the metric for \( X \) constructed in the proof of Theorem 3, then for each \( \varepsilon > 0 \) the collection \( \{ S(x, \varepsilon) : x \in X \} \) is finite.
BIBLIOGRAPHY


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Donald John Charles Bures, *Tensor products of W*-algebras* .......... 13
James Calvert, *Integral inequalities involving second order derivatives* ...... 39
Edward Dewey Davis, *Further remarks on ideals of the principal class* .......... 49
Le Baron O. Ferguson, *Uniform approximation by polynomials with integral coefficients I* ............................................. 53
Francis James Flanigan, *Algebraic geography: Varieties of structure constants* ......................................................... 71
Denis Ragan Floyd, *On QF − 1 algebras* ........................................ 81
David Scott Geiger, *Closed systems of functions and predicates* ............... 95
Delma Joseph Hebert, Jr. and Howard E. Lacey, *On supports of regular Borel measures* .................................................. 101
Martin Edward Price, *On the variation of the Bernstein polynomials of a function of unbounded variation* ........................................ 119
Louise Arakelian Raphael, *On a characterization of infinite complex matrices mapping the space of analytic sequences into itself* ............ 123
Louis Jackson Ratliff, Jr., *A characterization of analytically unramified semi-local rings and applications* ........................................... 127
Armond E. Spencer, *Maximal nonnormal chains in finite groups* ............. 167
Li Pi Su, *Algebraic properties of certain rings of continuous functions* ...... 175
G. P. Szegő, *A theorem of Rolle’s type in E^n for functions of the class C^1* 193
Giovanni Viglino, *A co-topological application to minimal spaces* ............ 197
B. R. Wenner, *Dimension on boundaries of ε-spheres* ............................ 201