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Two theorems for the $n$-dimensionality of metric spaces


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Two theorems for the $n$-dimensionality
of metric spaces*

by

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The purpose of this note is to establish two theorems that respectively give necessary and sufficient conditions for metric spaces to be $n$-dimensional.

1. We have proved earlier the following theorems [4] 1).

(I) A metric space $R$ has dim $\leq n$ if and only if we can introduce a topology-preserving metric $\rho$ into $R$ such that the spherical nbds ( = neighborhoods) $S_{1/\rho}(p)$, $i = 1, 2, \ldots$ of any point $p$ of $R$ have boundaries of dim $\leq n-1$ and such that $\{S_{1/\rho}(p) \mid p \in R\}$ is closure preserving 3) for every $i$.

(II) A metric space $R$ has dim $\leq n$ if and only if we can introduce a topology-preserving metric $\rho$ into $R$ such that

$$\dim B[S_{1/\rho}(F)] \leq n-1, \quad i = 1, 2, \ldots$$

for every closed set $F$ of $R$.4)

Our first problem is to refine these theorems as follows.

**Theorem 1.** A metric space $R$ has dim $\leq n$ if and only if we can introduce a topology-preserving metric $\rho$ into $R$ such that the spherical nbds $S_\varepsilon(p)$, $\varepsilon > 0$ of any point $p$ of $R$ have boundaries of dim $\leq n-1$ and such that $\{S_\varepsilon(p) \mid p \in R\}$ is closure preserving for any $\varepsilon > 0$.

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1) It follows from [8] that dim $R \leq n$ for a separable metric space $R$ if and only if we can introduce a metric into $R$ such that the boundary $B[S_\varepsilon(p)]$ of $S_\varepsilon(p) = \{q \mid \rho(p, q) < \varepsilon\}$ has dim $\leq n-1$ for almost all $\varepsilon$. See, for example, [9].

2) Dim $R$ denotes the covering dimension of $R$, but it coincides with the strong inductive dimension $\text{Ind} R$ by [2] and [8] if $R$ is metrizable.

3) A collection $\mathcal{A}$ of subsets of $R$ is called closure preserving if $\cup \{A \mid A \in \mathcal{A}\} = \cup \{A \mid A \in \mathcal{A}'\}$ for any subset $\mathcal{A}'$ of $\mathcal{A}$.

4) $S_{1/\rho}(F) = \{p \mid \rho(p, q) < 1/\rho \text{ for some } q \in F\}$. We expressed in [4] this theorem in a slightly different form, i.e. we proved it for every subset $F$ of $R$, but there is no essential difference.
PROOF. The if part of this theorem is implied by the if part of our previous Theorem (1). 5)

To show the only if part we let \( \dim \leq n \); then, as is easily seen, we can choose a sequence \( \{U_i|i = 0, 1, 2, \ldots\} \) of open coverings such that 6)

1) \( \{R\} = U_0 > U_1 > U_2 > U_3 > \ldots \),
2) \( \{S(p, U_m)|m = 0, 1, 2, \ldots\} \) is an nbd basis of each point \( p \) of \( R \),
3) \( S^2(p, U_{m+1}) \) intersects at most \( n+1 \) members of \( U_m \). Now we define \( S_{m_1 \ldots m_k}(U) \) for integers \( m_1, m_2, \ldots, m_k \) with \( 1 \leq m_1 < m_2 < \ldots < m_k \) and for \( U \in U_m \), by

\[
S_{m_1}(U) = U, \quad m_1 \geq 0;
\]
\[
S_{m_1 \ldots m_k}(U) = S^2(S_{m_1 \ldots m_{k-1}}(U), U_{m_k}), \quad 1 \leq m_1 < m_2 < \ldots < m_k, \quad k \geq 2.
\]

Then we define open coverings of \( R \) by

\[
\mathcal{S}_{m_1} = U_{m_1}, \quad m_1 \geq 0
\]
\[
\mathcal{S}_{m_1 \ldots m_k} = \{S_{m_1 \ldots m_k}(U)|U \in U_{m_1}\}, \quad 1 \leq m_1 < m_2 < \ldots < m_k, \quad k \geq 2,
\]

to define a non-negative valued function \( \rho(x, y) \) on \( R \times R \) by

\[
\rho(x, y) = \inf\{1/2^{m_1} + \ldots + 1/2^{m_k}|y \in S(x, \mathcal{S}_{m_1 \ldots m_k})\}.
\]

We have shown [6], [7] that this function \( \rho(x, y) \) is a topology-preserving metric of \( R \). 7) We can now prove that \( \rho \) is the desired metric.

For any countable sequence \( m_1, m_2, \ldots \) of integers with \( 1 \leq m_1 < m_2 < \ldots \) we define open sets \( S_{m_1 m_2 \ldots}(U) \), \( U \in U_{m_1} \) by

\[
S_{m_1 m_2 \ldots}(U) = \bigcup_{k=1}^{\infty} S_{m_1 \ldots m_k}(U)
\]

and open coverings \( \mathcal{S}_{m_1 m_2 \ldots} \) by

\[
\mathcal{S}_{m_1 m_2 \ldots} = \{S_{m_1 m_2 \ldots}(U)|U \in U_{m_1}\}.
\]

5) The proof of sufficiency in [4] should be read as follows: First, let us note that \( \{BS_{1/2i}(p)|p \in A\} \) is closure preserving in \( B[ U \cup \{S_{1/2i}(p)|p \in A\}] \ldots \). Hence \( \dim B[ U \cup \{S_{1/2i}(p)|p \in A\}] \leq n-1 \) follows from \( \dim BS_{1/2i}(p) \leq n-1, p \in A \) by virtue of a theorem due to Nagami.

4) Let \( \mathcal{A}, A, p \) be a covering, a set and a point of \( R \) respectively. Then \( S(p, \mathcal{A}) = \cup\{U|p \in U \in \mathcal{A}\}, S(A, \mathcal{A}) = \cup\{U|A \in U \in \mathcal{A}\} \subset R-A \), \( S^n(p, \mathcal{A}) = S(S^{n-1}(p, \mathcal{A}), \mathcal{A}), S^n(A, \mathcal{A}) = S(S^{n-1}(A, \mathcal{A}), \mathcal{A}), S^\infty = \{S(U, \mathcal{A})|U \in \mathcal{A}\}. \)

7) We proved in [6], [7] \( \rho(x, y) \) satisfied another condition which also characterized the dimension of \( R \). That condition was simplified in separable cases by [1].
Suppose
\[ 0 < \varepsilon = \frac{1}{2^{m_1}} + \frac{1}{2^{m_2}} + \ldots \]
and
\[ 1 \leq m_1 < m_2 < \ldots ; \]
then we can assert

(A) \[ S_\varepsilon(p) = S(p, \mathcal{E}_{m_1 m_2 \ldots}). \]

For if \( q \not\in S(p, \mathcal{E}_{m_1 m_2 \ldots}) \), \( k = 1, 2, \ldots , \) then \( \rho(p, q) \geq 1/2^{m_1} + 1/2^{m_2} + \ldots \) which means \( q \not\in S_\varepsilon(p) \). Hence we get
\[ S_\varepsilon(p) \subseteq S(p, \mathcal{E}_{m_1 m_2 \ldots}) \]
from
\[ \mathcal{E}_{m_1 \ldots m_k} < \mathcal{E}_{m_1 \ldots m_{k+1}}. \]

Conversely, if \( q \in S(p, \mathcal{E}_{m_1 m_2 \ldots}) \), then there exists \( U \in \mathcal{U}_{m_1} \) such that \( p, q \in S_{m_1 m_2 \ldots}(U) \). In view of the definition of \( S_{m_1 m_2 \ldots}(U) \), we get \( p, q \in S_{m_1 \ldots m_k}(U) \) for some \( k \geq 1 \). Hence \( \rho(p, q) \leq 1/2^{m_1} + + \ldots + 1/2^{m_k} < \varepsilon \), which means \( q \in S_\varepsilon(p) \), and hence
\[ S(p, \mathcal{E}_{m_1 m_2 \ldots}) \subseteq S_\varepsilon(p). \]
Thus we can conclude
\[ S_\varepsilon(p) = S(p, \mathcal{E}_{m_1 m_2 \ldots}). \]

To show \( \dim B[S_\varepsilon(p)] \leq n-1 \) we shall prove

(B) \[ \operatorname{ord} \mathcal{E}_{m_1 m_2 \ldots} \leq n+1 \text{ for every } \mathcal{E}_{m_1 m_2 \ldots}. \]

To this end we shall inductively prove
\[ S^3(S_{m_1 \ldots m_{k-1}}(U), \mathcal{U}_{m_k}) \subseteq S^3(U, \mathcal{U}_{m_{k+1}}), \quad k \geq 2. \]
This proposition is clearly valid for \( k = 2 \) since \( \mathcal{U}_{m_2} < \mathcal{U}_{m_{1+1}} \) is implied by \( m_2 \geq m_1+1 \).

Assume the validity for \( k = k \); then
\[ S^3(S_{m_1 \ldots m_k}(U), \mathcal{U}_{m_{k+1}}) = S^3(S^3(S_{m_1 \ldots m_{k-1}}(U), \mathcal{U}_{m_k}), \mathcal{U}_{m_{k+1}}) \]
\[ \subseteq S^3(S_{m_1 \ldots m_{k-1}}(U), \mathcal{U}_{m_k}) \subseteq S^3(U, \mathcal{U}_{m_{1+1}}) \]
follows from \( \mathcal{U}_{m_{k+1}} < \mathcal{U}_{m_k} \) combined with the inductive assumption. Hence we get

(C) \[ S_{m_1 m_2 \ldots}(U) \subseteq S^3(U, \mathcal{U}_{m_{1+1}}). \]
Since by \( 3 \) each \( S(p, \mathcal{U}_{m_{1+1}}^*) \) intersects at most \( n+1 \) sets of \( \mathcal{U}_{m_1} \),
each point \( p \) of \( R \) is contained in at most \( n+1 \) of \( S^3(U, \cup_{m_l+1}) \), \( U \in \cup_{m_l} \). This combined with (C) implies (B).

Now let us turn to the proof of \( \dim B[S_\varepsilon(p)] \leq n-1 \). Let \( q \in B[S_\varepsilon(p)] \); then we can express the positive number \( \varepsilon(\leq 1) \) in the form of

\[
\varepsilon = \frac{1}{2^{m_1}} + \frac{1}{2^{m_2}} + \ldots
\]

for some countable sequence \( m_1, m_2, \ldots \) of integers with \( 1 \leq m_1 < m_2 < \ldots \). We can prove

\[
\text{ord}_q \cup_{m_k} \leq n^8, \quad k = 1, 2, \ldots
\]

For, if we suppose \( q \in U_i \in \cup_{m_k}, i = 1, \ldots, n+1 \), then by virtue of (A), there exists \( U \in \cup_{m_k} \) such that

\[
U \subset S_\varepsilon(p), \quad S_{m_{k+1}} \cap (\bigcap_{i=1}^{n+1} U_i) \neq \emptyset.
\]

But this implies

\[
\text{ord} \cup_{m_k} \geq n+2
\]

and hence it contradicts (B). Thus \( \{\cup_{m_1}, \cup_{m_2}, \ldots\} \) can be regarded as a sequence of open coverings of \( B[S_\varepsilon(p)] \) satisfying

\[
\cup_{m_1} \supset \cup_{m_2} \supset \cup_{m_3} \supset \ldots
\]

\( \{S(p, \cup_{m_k})|k = 1, 2, \ldots\} \) is an nbd basis of \( p \),

\[
\text{ord} \cup_{m_k} \leq n, \quad k = 1, 2, \ldots
\]

Therefore we can conclude

\[
\dim B[S_\varepsilon(p)] \leq n-1
\]

by one of our \( n \)-dimensionality theorems\(^6\).

Finally, we shall show that \( \{S_\varepsilon(p)|p \in R\} \) is closure preserving for any \( \varepsilon > 0 \). It follows from (A) and (B) that each \( S_\varepsilon(p) \) is a finite sum of sets of \( \cup_{m_1} \ldots \) if \( \varepsilon = 1/m_1 + 1/m_2 + \ldots \). Hence closure preserving property of \( \cup_{m_1} \ldots \) implies that of \( \{S_\varepsilon(p)|p \in R\} \).

To see the closure preserving of \( \cup_{m_1} \ldots \) we should notice the condition (3) which implies that each set of \( \cup_{m_1} \) intersects at most \( n+1 \) sets of \( S^3(U, \cup_{m_l+1})|U \in \cup_{m_l} \}. \) Hence, in view of (C), we can conclude that each set of \( \cup_{m_l+1} \) intersects at most \( n+1 \) sets

\(^6\) Let \( \mathcal{A} \) be a collection of sets of \( R \) and \( q \) a point of \( R \). Then \( \text{ord}_q \mathcal{A} \) denotes the number of elements of \( \mathcal{A} \) which contain \( q \). Then \( \text{ord} \mathcal{A} = \max\{\text{ord}_q \mathcal{A}|q \in R\} \).

\(^7\) [7], Theorem 3.
of $\mathcal{E}_{m_1 m_2 \ldots}$. Hence $\mathcal{E}_{m_1 m_2 \ldots}$ is locally finite, and accordingly closure preserving. Thus $\{S_\varepsilon(p)|p \in R\}$ is closure preserving, which completes the proof of this theorem.

The metric in this theorem is rather peculiar considering that the usual metric of Euclidean space does not satisfy the closure preserving condition, but the metric in the following corollary will be more reasonable.

**Corollary 1.** A metric space $R$ has $\dim \leq n$ if and only if we can introduce a topology-preserving metric $\rho$ into $R$ such that

$$\dim B[S_\varepsilon(F)] \leq n-1, \varepsilon > 0$$

for any closed set $F$ of $R$.

**Proof.** We can easily deduce it from Theorem 1 as we have deduced (II) from (I).\(^{10}\)

**Corollary 2.** A metric space $R$ has $\dim \leq n$ if and only if we can introduce a topology-preserving metric $\rho$ into $R$ such that

$$\dim C_\varepsilon(\phi) \leq n-1$$

for any irrational (or for almost all) $\varepsilon > 0$ and for any point $p$ of $R$ and such that $\{C_\varepsilon(p)|p \in R\}$ is closure preserving for any irrational (or for almost all) $\varepsilon > 0$, where

$$C_\varepsilon(p) = \{q|\rho(p, q) = \varepsilon\}.$$

**Proof.** The sufficiency of condition is clear.

Referring to the necessity we can show the metric in the proof of Theorem 1 is the required one. To see this it suffices to prove

$$C_\varepsilon(p) = B[S_\varepsilon(p)]$$

for any irrational $\varepsilon > 0$. Since $B[S_\varepsilon(p)] \subset C_\varepsilon(p)$ is clear, we let $q$ be a given point with $q \notin B[S_\varepsilon(p)]$ to establish the inverse. If $q \in S_\varepsilon(p)$, then $q \notin C_\varepsilon(p)$ is obvious, so we suppose $q \notin S_\varepsilon(p)$. Let $\varepsilon = 1/2^{m_1+1}/2^{m_2+\ldots}$; then by (A) in the proof of Theorem 1

$$S_\varepsilon(p) = S(p, \mathcal{E}_{m_1 m_2 \ldots}).$$

Since $\varepsilon$ is irrational, we can choose a sufficiently large $m_i$ such that

$$S(q, U_{m_i}) \cap S(p, \mathcal{E}_{m_1 m_2 \ldots}) = \phi$$

$$m_{i+1} \geq m_i + 2.$$\(^{10}\) See [4].
Then it is easily seen that

\[ q \notin S(p, \mathcal{C}_{m_1 \ldots m_t m_{t+1}}) . \]

Hence

\[ \rho(p, q) \geq \frac{1}{2m_1} + \ldots + \frac{1}{2m_t} + \frac{1}{2m_{t+1}} > \varepsilon , \]

which means \( q \notin C_\varepsilon(p) \), and hence

\[ C_\varepsilon(p) \subset B[S_\varepsilon(p)] . \]

Thus \( C_\varepsilon(p) = B[S_\varepsilon(p)] \) is proved for every irrational \( \varepsilon \).

In view of this proof we see that

\[ C_\varepsilon(p) = B[S_\varepsilon(p)] \]

holds not only for irrational numbers but for any positive number

\[ \varepsilon = \frac{1}{2^{m_1}} + \frac{1}{2^{m_1}} + \ldots \]

such that for any positive \( m \) there exists \( m_i \) satisfying \( m_i < m_{i+1} - 2 \).

**Corollary 3.** A metric space \( R \) has \( \dim \leq n \) if and only if we can introduce a topology-preserving metric \( \rho \) into \( R \) such that for all irrational (or for almost all) positive numbers \( \varepsilon \) and for any closed set \( F \) of \( R \), \( \dim C_\varepsilon(F) \leq n - 1 \), where

\[ C_\varepsilon(F) = \{ p | \rho(p, F) = \varepsilon \} . \]

**Proof.** The sufficiency is clear. Referring to the necessity we can easily see that the metric in the proof of Corollary 2 satisfies the desired condition.

2. Our next problem is to give a new type of condition for \( n \)-dimensionality by use of the new terminology 'rank' of collection of sets.

**Definition 1.** Two subsets \( A \) and \( B \) of \( R \) are called independent if \( A \cap B \) and \( B \cap A \). A collection of subsets is called independent if any two members of it are independent.

**Definition 2.** Let \( \mathcal{U} \) be a collection of subsets of a space \( R \) and \( p \) a point of \( R \). Then \( \operatorname{rank}_p \mathcal{U} \) is the largest integer \( n \) such that there are \( n \) independent members of \( \mathcal{U} \) which contain \( p \). Moreover \( \operatorname{rank} \mathcal{U} = \max \{ \operatorname{rank}_p \mathcal{U} | p \in R \} \).

In view of this definition we clearly see \( \operatorname{rank}_p \mathcal{U} \leq \operatorname{ord}_p \mathcal{U} \) for any point \( p \) and collection \( \mathcal{U} \) of subsets, and accordingly \( \operatorname{rank} \mathcal{U} \leq \operatorname{ord} \mathcal{U} \).

**Definition 3.** Let \( A \) and \( B \) be two subsets of \( R \). If \( A \) meets \( B \) as well as \( R - B \), then we say \( A \) overflows \( B \).
Now we can prove the following.

**THEOREM 2.** A metric space has dim \( \leq n \) if and only if it has an open basis \( \mathcal{U} \) with rank \( \mathcal{U} \leq n+1 \).

**PROOF.** To begin with, let us prove the if part by induction. Let \( \mathcal{U} \) be an open basis with rank \( \leq 1 \). Suppose \( F \) and \( G \) are disjoint closed sets of \( R \). Then we let

\[
U = \bigcup \{ U' \mid U' \in \mathcal{U}, \ U' \cap F \neq \emptyset, \ U' \cap G = \emptyset \}.
\]

Since \( \mathcal{U} \) is an open basis of \( R \), \( U \) is an open set satisfying

\[
F \subset U \subset R - G.
\]

If \( p \notin U \), then there exists \( U' \in \mathcal{U} \) such that \( p \in U' \subset R - F \). If we assume \( U' \cap U \neq \emptyset \), then \( U' \cap U'' \neq \emptyset \) for some \( U'' \in \mathcal{U} \) with \( U'' \cap F \neq \emptyset \). Since \( U' \) and \( U'' \) are clearly independent, we reach a contradiction to rank \( \mathcal{U} \leq 1 \). Hence \( U' \cap U = \emptyset \), which means that the open set \( U \) is closed in \( R \). Thus we get dim \( R \leq 0 \).

Suppose we have proved that the existence of an open basis with rank \( \leq n \) implies dim \( R \leq n - 1 \). Then we suppose \( R \) has an open basis \( \mathcal{U} \) with rank \( \mathcal{U} \leq n+1 \). Let \( F \) and \( G \) be two disjoint closed sets of \( R \). Then we define an open set \( U \) by

\[
U = \bigcup \{ U' \mid U' \in \mathcal{U}, \ U' \cap F \neq \emptyset, \ U' \cap G = \emptyset \}.
\]

\( U \) clearly satisfies

\[
F \subset U \subset R - G.
\]

We shall prove that \( \mathcal{U}' = \{ U' \mid U' \in \mathcal{U}, \ U' \cap F = \emptyset \} \) restricted to \( B[U] \) makes an open basis of \( B[U] \) satisfying rank \( \mathcal{U}' \leq n \).

It is clear that \( \mathcal{U}' \) is an open basis of \( B[U] \) if restricted to \( B[U] \).

Thus all we have to show is that rank\(_p\) \( \mathcal{U}' \leq n \) for a given point \( p \in B[U] \). Suppose the contrary, i.e. \( U_1, \ldots, U_{n+1} \) are independent sets of \( \mathcal{U}' \) which contain \( p \). Since \( p \in B[U] \), we get

\[
g \in U_1 \cap \ldots \cap U_{n+1} \cap U \neq \emptyset.
\]

Thus

\[
g \in U_1 \cap \ldots \cap U_{n+1} \cap U'
\]

for some \( U' \in \mathcal{U} \) with \( U' \cap F \neq \emptyset, \ U' \subset U \). Since \( U_i \cap F = \emptyset, \ U_i \cap (R - U') \neq \emptyset \), \( i = 1, \ldots, n+1 \), \( U_1, \ldots, U_{n+1} \) and \( U' \) are independent contradicting rank \( \mathcal{U} \leq n+1 \). Thus we get rank\(_p\) \( \mathcal{U}' \leq n \), and hence dim \( B[U] \leq n - 1 \) follows from the inductive assumption. Therefore dim \( R \leq n \) is proved.

To prove the only if part we suppose \( R \) is a metric space with
dim $R \leq n$. $R$ can be decomposed into $n+1$ zero-dimensional subspaces $A_i$, $i = 1, \ldots, n+1$. Let us apply one of our previous results ¹¹) to the present problem to get a locally finite open covering $\mathcal{U}_1$ with mesh $\mathcal{U}_1 < 1$ such that

$$\text{ord}_p B[\mathcal{U}_1] \leq i-1$$ ¹²) for every $p \in A_i$.

Let

$$B_k = \{p \mid \text{ord}_p B[\mathcal{U}_1] \geq k\}, \quad k = 0, 1, \ldots, n;$$

then it follows from $B_k \subset A_{k+1} \cup \ldots \cup A_{n+1}$ that

$$\dim B_k \leq n-k, \quad k = 0, 1, \ldots, n.$$ ¹³)

Each $B_k$ is closed since $B[\mathcal{U}_1]$ is locally finite. Moreover $B_k \subset B_{k-1}$ is clear from the definition of $B_k$. Let $\mathcal{G}$ be an open covering with mesh $\frac{1}{2}$. For every point $p$ of $B_k - B_{k+1}$ we choose an open nbd $U(p)$ of $p$ such that $U(p)$ overflows just $k$ sets of $\mathcal{U}_1$. We see the existence of such an nbd in view of the definition of $B_k$. Then

$$\mathcal{W}_k = \{U(p) \mid p \in B_k - B_{k+1}\}$$

is a collection of open sets which covers $B_k - B_{k+1}$. Now we can define a locally finite open covering $\mathcal{W} < \mathcal{G}$ such that $\mathcal{W} = \bigcup_{k=0}^{n} \mathcal{W}_k$, $\mathcal{W}_k \supset \mathcal{W}_{k-1}$, ord $\mathcal{W}_k \leq k+1$, $\mathcal{W}_k - \mathcal{W}_{k-1} < \mathcal{W}_{n-k}$ ¹³) and $\mathcal{W}_k$ covers $B_{n-k}$. To realize it we shall show, by induction, that for any $m$ with $0 \leq m \leq n$ we can define locally finite open collections $\mathcal{W}_m$ of $R$ such that

$$\mathcal{W}_m = \bigcup_{k=0}^{m} \mathcal{W}_k, \quad \mathcal{W}_k \supset \mathcal{W}_{k-1}, \quad \text{ord} \mathcal{W}_k \leq k+1, \quad \mathcal{W}_k - \mathcal{W}_{k-1} < \mathcal{W}_{n-k}, \quad \mathcal{W}_k \subset \mathcal{G}$$

and such that $\mathcal{W}_k$ covers $B_{n-k}$.

For $m = 0$ we choose, by use of dim $B_n \leq 0$, an open covering $\mathcal{Q}$ of $B_n$ with ord $\mathcal{Q} \leq 0$, $\mathcal{Q} < \mathcal{W}_n \wedge \mathcal{G}$. It is easy to see that $\mathcal{Q}$ can be extended to a locally finite collection $\mathcal{W}_0$ of open sets of $R$ such that

$$\text{ord} \mathcal{W}_0 \leq 1, \quad \mathcal{W}_0 < \mathcal{W}_n \wedge \mathcal{G}$$

and such that

$$\{P \cap B_n \mid P \in \mathcal{W}_0\} = \mathcal{Q}.$$ ¹¹) [5] Lemma 2.1.

¹²) Let $\mathfrak{A}$ be a collection of subsets of $R$; then mesh $\mathfrak{A} = \sup\{\text{diameter } U \mid U \in \mathfrak{A}\}$, $B(\mathfrak{A}) = \{B[U] \mid U \in \mathfrak{A}\}$.

¹³) We suppose $\mathcal{W}_n = \{U(p) \mid p \in B_n\}$, $\mathcal{W}_{-1} = \phi$. ⁰
Now let us suppose we have defined $\mathcal{P}_m$ at our desire. Then let

$$
\mathcal{P}_k = \{P_\alpha | \alpha < \alpha_{k+1} \}, \quad k = 0, 1, \ldots, m.
$$

Since $\dim B_{n-m-1} \leq m+1$, we can find a locally finite open covering $\mathcal{M}$ of $B_{n-m-1}$ satisfying

$$\text{ord } \mathcal{M} \leq m+2, \quad \mathcal{M} \subset \mathcal{P}_m \cup \mathcal{W}_{n-m-1}, \quad \mathcal{M} \subset \mathcal{G}.$$ 

It is easy to see that $\mathcal{M}$ can be extended to a locally finite collection $\mathcal{M}$ of open sets of $R$ such that

$$\text{ord } \mathcal{M} \leq m+2, \quad \mathcal{M} \subset \mathcal{P}_m \cup \mathcal{W}_{n-m-1}, \quad \mathcal{M} \subset \mathcal{G}.$$ 

We let

$$
\begin{align*}
P_\alpha' &= \cup \{M | M \in \mathcal{M}, M \subset P_\alpha, M \not\subset P_\beta \text{ for any } \beta < \alpha \}, \\
\mathcal{P}_k' &= \{P_\alpha' | \alpha < \alpha_{k+1} \}, \quad k = 0, 1, \ldots, m, \\
\mathcal{P}_{m+1}' &= \mathcal{P}_m \cup \{M | M \subset P_\alpha \text{ for any } \alpha < \alpha_{m+1} \}.
\end{align*}
$$

Then $\mathcal{P}_{m+1}' = \bigcup_{k=0}^{m+1} \mathcal{P}_k'$ is the desired locally finite open collection which covers $B_{n-m-1}$. The only problem is to show that $\mathcal{P}_k'$ covers $B_{n-k}$ but this can be easily deduced from the fact that each element of $\mathcal{P}_m - \mathcal{P}_k$ does not meet $B_{n-k}$ since

$$\mathcal{P}_m - \mathcal{P}_k \subset \mathcal{W}_{n-k-1} \cup \ldots \cup \mathcal{W}_{n-m}$$

and each element of $\mathcal{W}_{n-k-1} \cup \ldots \cup \mathcal{W}_{n-m}$ does not meet $B_{n-k}$ by the definition of $\mathcal{W}_i$. Each element of $\mathcal{W}_{n-m-1}$, of course, does not meet $B_{n-k}$, either. Let $p$ be a given point of $B_{n-k}$; then $p \in M$ for some $M \in \mathcal{M}$. Since $\mathcal{M} \subset \mathcal{P}_m \cup \mathcal{W}_{n-m-1}$, it follows from the above remark that $p \in M \subset P$ for some $P \in \mathcal{P}_k$, and hence $M \subset P'$ for some $P' \in \mathcal{P}_k'$. Thus we can define the desired locally finite open covering $\mathcal{P}$ of $R$. Let $\mathcal{P} = \{P_\gamma | \gamma \in \Gamma \}$, $\mathcal{P}_k = \{P_\gamma | \gamma \in \Gamma_k \}$, $k = 0, \ldots, n$; then there exists an open covering $\mathcal{V} = \{V_\gamma | \gamma \in \Gamma \}$ of $R$ such that $\mathcal{V}_\gamma \subset P_\gamma$, $\gamma \in \Gamma$. Now again by use of the lemma in [5], we can define an open covering $\mathcal{U}_2 = \{U_\gamma | \gamma \in \Gamma \}$ of $R$ satisfying $\mathcal{V}_\gamma \subset U_\gamma \subset P_\gamma$, $\gamma \in \Gamma$ and

$$\text{ord}_p \mathcal{B}[\mathcal{U}_1 \cup \mathcal{U}_2] \leq i-1 \quad \text{for every } p \in A_i.$$ 

In view of the process of definition it is clear that

$$\mathcal{U}_2 \subset \mathcal{G}, \quad \text{ord } \mathcal{U}_k \leq k+1, \quad \mathcal{U}_k - \mathcal{U}_k-1 \subset \mathcal{W}_{n-k},$$

where $\mathcal{U}_k = \{U_\gamma | \gamma \in \Gamma_k \}$.

Let us finally show rank $\mathcal{U}_1 \cup \mathcal{U}_2 \leq n+1$.

Suppose

$$p \in U_1 \cap \ldots \cap U_k \cap U_{k+1} \cap \ldots \cap U_{n+2}$$
for $n+2$ independent sets

$$U_1, \ldots, U_k \in \mathcal{U}_1 \quad \text{and} \quad U_{k+1}, \ldots, U_{n+2} \in \mathcal{U}_2.$$  

Then, since $\operatorname{ord} \mathcal{U}^{n-k} \leq n-k+1$, at most one of $U_{k+1}, \ldots, U_{n+2}$ does not belong to $\mathcal{U}^{n-k}$. For example, let

$$U_{k+1} \in \mathcal{U}^{l+1}-\mathcal{U}^l \quad \text{for some} \quad l \geq n-k.$$  

Since $\mathcal{U}^{l+1}-\mathcal{U}^l < \mathcal{B}_{n-l-1}$ and each member of $\mathcal{B}_{n-l-1}$ overflows just $n-l-1$ sets of $\mathcal{U}_{1}$, $U_{k+1}$ overflows at most $n-l-1$ sets of $\mathcal{U}_{1}$. Since $n-l-1 \leq k-1$, $U_{k+1}$ overflows at most $k-1$ sets of $\mathcal{U}_{1}$. On the other hand, since $U_1, \ldots, U_k, U_{k+1}$ are independent and have a common point $p$, $U_{k+1}$ must overflow $k$ sets $U_1, \ldots, U_k$ of $\mathcal{U}_1$, which is a contradiction. Thus we can conclude

$$\operatorname{rank} \mathcal{U}_1 \cup \mathcal{U}_2 \leq n+1.$$  

By repeating this process again we can define the third locally finite open covering $\mathcal{U}_3$ of $R$ such that

$$\operatorname{mesh} \mathcal{U}_3 < \frac{1}{3}, \quad \operatorname{rank} \mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3 \leq n+1$$  

and

$$\operatorname{ord}_p B[\mathcal{U}_1 \cup \mathcal{U}_2 \cup \mathcal{U}_3] \leq i-1 \quad \text{for every} \quad p \in A_i.$$  

Eventually, by repeating this process, we get a sequence $\mathcal{U}_1, \mathcal{U}_2, \mathcal{U}_3, \ldots$ of open coverings of $R$ satisfying

$$\operatorname{mesh} \mathcal{U}_i < \frac{1}{i}, \quad i = 1, 2, \ldots, \quad \operatorname{rank} \bigcup_{i=1}^\infty \mathcal{U}_i \leq n+1.$$  

Thus $\mathcal{U} = \bigcup_{i=1}^\infty \mathcal{U}_i$ is the desired open basis of $R$ with $\operatorname{rank} \mathcal{U} \leq n+1$.

The following is a direct consequence of this theorem.

**Corollary 4.** A metric space $R$ has an open basis $\mathcal{U}$ with $\operatorname{rank}_p \mathcal{U} < +\infty$ at every point $p$ of $R$ if and only if $R$ is strongly countable-dimensional $^{14}$), i.e. it is the countable sum of finite-dimensional closed sets.

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$^{14}$ See [5].
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