AN ARCWISE CONNECTED DENSE HAMEL BASIS
FOR HILBERT SPACE

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Abstract. This paper shows if \( X \) is an infinite dimensional Banach space, \( X \) contains a linearly independent arc. Also based on the continuum hypothesis, that if \( X \) is an infinite dimensional Banach space and card \( X = c \), then \( X \) contains a dense arcwise connected Hamel basis.

The main result of this paper is that any infinite dimensional Banach space with the same cardinal number as the real line contains an arcwise connected dense Hamel basis. The proof of this result uses the continuum hypothesis. Two lemmas are proved which are of independent interest. Lemma 1 shows that a large class of subspaces of normed linear spaces are of the 1st category. In this connection, Hausdorff showed that any infinite dimensional real Banach space contains a second category linear subspace which is not complete under any equivalent norm [2]. Lemma 2 deals with homeomorphisms in the space \( C(I, X) \) of mappings from the unit interval \( I \) into an infinite dimensional Banach space \( X \). It is known that this set of homeomorphisms is dense in \( C(I, X) \); and G. G. Johnson [3] and [4], while working on problem 4 in Halmos’ book [1] has shown that if \( f \) is a homeomorphism in \( C(I, X) \) such that each two nonoverlapping chords of \( f([0, 1]) \) are orthogonal, then the nonzero values of \( f \) are linearly independent. It follows from Lemma 2 that the set of all homeomorphisms in \( C(I, X) \) with linearly independent range is, in fact, a dense \( G_\delta \) in \( C(I, X) \).

Lemma 1. If \( X \) is an infinite dimensional normed linear space which is spanned by a subset of a \( \sigma \)-compact set, \( X \) is first category.

Proof. Let \( B_1, B_2, \ldots \) be compact subsets of \( X \) so that \( X = \bigcup_{i=1}^{\infty} B_i \) and \( B_i \subseteq B_{i+1} \). Let \( M(i, j) = \{ y \mid y = c_1x_1 + \cdots + c_ix_i \text{ where } |c_k| \leq i \text{ and } x_k \in B_j \text{ for } k \in \{ 1, \ldots, i \} \} \).

Because \( B_j \) is compact, \( M(i, j) \) is compact. Since \( X \) is infinite dimensional, it is not locally compact. Therefore \( M(i, j) \) contains no open sets. But \( X \) is the union of \( M(i, j) \) over all positive \( i \) and \( j \). Therefore \( X \) is first category.

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Lemma 2. If $X$ is an infinite dimensional Banach space and $X'$ is a linear subspace of $X$ which has a $\sigma$-compact Hamel basis then there exists a homeomorphism $h : I \to X$ such that $L[h(I)] \cap X' = 0$ and $h(I)$ is linearly independent. Furthermore, the set of continuous functions $f$ from $I$ into $X$ such that $f(I)$ is linearly dependent or $f$ is not one-to-one is first category.

Proof. Let $A_1, A_2, \ldots$ be a basis of connected open sets for the open sets of $I$. Let $B_1, B_2, \ldots$ be compact subsets of $X$ so that $B_1 \subseteq B_2 \subseteq \cdots$ and the union of the $B_i$'s contains a Hamel basis for $X'$. Let $M(i, j) = \{ y = c_1x_1 + \cdots + c_i x_i \mid c_k \leq i \text{ and } x_k \in B_j \text{ for } k \in \{1, \ldots, i\} \}$.

Let $M(i, j, i_1, \ldots, i_l) = \{ f \in C(I, X) \mid \text{there exist } y_k \in c \mid A_{i_k}, d_k \in [-1, 1] \text{ such that } d_1 = 1 \text{ and } d_1 f(y_1) + \cdots + d_l f(y_l) \text{ belongs to } M(i, j) \}$ where if $c \mid A_{i_k} \cap c \mid A_{i_r} \neq \emptyset$, $r = k$.

Let $M(i, j, i_1, \ldots, i_l) = \emptyset$ if $c \mid A_{i_k} \cap c \mid A_{i_r} \neq \emptyset$ for some $r \neq k$.

It is clear $M(i, j, i_1, \ldots, i_l)$ is closed in $C(I, X)$.

Now assume $f \in M(i, j, i_1, \ldots, i_l)$.

Since $f(I) \cup B_j$ is compact, $L[f(I) \cup B_j]$ is first category. Let $\varepsilon_1 \in L[f(I) \cup B_j]$. Let $D_1$ be an open connected subset of $R$ such that $D_1$ contains $c \mid A_{i_1} \cap c \mid A_{i_j} = \emptyset$ for $j \in \{2, \ldots, l\}$.

Let $d_1$ be the midpoint of $D_1$ and $r_1$ the radius of $D_1$.

Let $f_1(x) = f(x)$ for $x \in I - D_1$.

Let $f_1(x) = f(x) + (r_1 - \vert x - d_1 \vert) \varepsilon_1 / 2^i$ for $x \in I \cap D_1$.

It is clear $f_1 \in M(i, j, i_1, \ldots, i_l)$ and that $f \rightarrow f_1$.

Therefore $M(i, j, i_1, \ldots, i_l)$ is nowhere dense.

Note the union of all these sets would include all functions in $C(I, X)$ that are not one-to-one or that map $I$ onto a linearly dependent set.

Since $C(I, X)$ is complete, there exists a point $h$ not in that set. This function $h$ will satisfy the conclusion.

Theorem 3. If $X$ is an infinite dimensional Banach space, $\text{card } X = c$ and the continuum hypothesis is satisfied, then $X$ contains a dense arcwise connected Hamel basis.

Proof. Let $A$ be a Hamel basis for $X$. Let $B$ be a basis for the open sets of $X$ so that $\text{card } B = c$. By the continuum hypothesis, $\text{card } B = \text{card } A = c$, the smallest uncountable cardinal number. Well order $A$ so that every element of $A$ has at most a countable number of predecessors. Let $f$ be a one-to-one function from $A$ onto $B$. Let $a_1$ be the first element of $A$. Let $b_1 \in f(a_1) - L[\{a_1\}]$. By Lemma 2, there exists a homeomorphism $h''$ of $I$ into $X$ such that $L[h''(I)] \cap L[\{a_1, b\}] = 0$ and $h''(I)$ is linearly independent.
Let \( h'(x) = xh''(x) + (1-x)a_1 \) for \( x \in I \).
Let \( h(x) = (1-x)h'(x) + xb_1 \).
Let \( A_{a_1} = h(I) \).
\( A_{a_1} \) is a linearly independent arc from \( a_1 \) to \( b_1 \).
Let \( a \in A \). Assume now for all \( b \in A \) such that \( b < a \),
(1) \( A_b \) is a linearly independent set.
(2) \( A_b \) contains a point of \( f(b) \), and \( L[A_b] \) contains \( b \).
(3) \( A_b \) is a countable union of arcs each of which contains \( a_1 \).
(4) If \( c \in A \) and \( c < b \), \( A_c \subseteq A_b \).

Let \( C = \bigcup_{b < a} A_b \). Using Lemma 1, let \( f'(a) \subseteq f(a) - L[C] \).
By Lemma 2, there exists a homeomorphism \( h'' \) of \( I \) into \( X \) such that \( h''(I) \) is linearly independent and \( L[h''(I)] \cap L[C \cup f'(a)] = 0 \).
Let \( h''(x) = xh''(x) + (1-x)a_1 \) for \( x \in I \).
Let \( h'(x) = (1-x)h'(x) + xf'(a) \).
If \( a \in L[C \cup h(I)] \), let \( A_a = C \cup h(I) \).
If \( a \notin L[C \cup h(I)] \), let \( g'' \) be a homeomorphism of \( I \) into \( X \) so that \( g''(I) \) is linearly independent and that \( L[g''(I)] \cap L[C \cup h_a(I) \cup a] = 0 \).
Let \( g''(x) = xg''(x) + (1-x)a_1 \) for \( x \in I \).
Let \( g'(x) = (1-x)g'(x) + xa \) for \( x \in I \).
Let \( A_a = B \cup h_a(I) \cup g_a(I) \).
In either case \( A_a \) is a countable union of arcs each having \( a_1 \) as an endpoint, \( a \in L[A_a] \), there is a point appearing both in \( f(a) \) and \( A_a \) and \( A_a \) is linearly independent.
Therefore \( H = \bigcup_{a \in A} A_a \) is a Hamel basis for \( X \) which is dense and arcwise connected.

References


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