MINIMAL COMPLEMENTARY SETS

BY

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ABSTRACT. Let G be a group on which a measure m is defined. If A, B ⊂ G we define A ⊕ B = C = \{c|c = a + b, a ∈ A, b ∈ B\}. By A_k ⊂ G we denote a subset of G consisting of k elements. Given A_k we define s(A_k) = \inf\{m|B ⊂ G, A_k ⊕ B = G\}, and c_k = \sup_{A_k ⊂ G} s(A_k). Theorems 1, 2, and 3 deal with the problem of determining c_k.

In the dual problem we are given B, m(B) > 0, and required to find minimal A such that A ⊕ B = G or, sometimes, m(A ⊕ B) = m(G). Theorems 5 and 6 deal with this problem.

Let A and B be sets of nonnegative integers, with 0 ∈ A. The set B is called a complement of A if each nonnegative integer is expressible in the form a + b (a ∈ A, b ∈ B). One of the basic problems in additive number theory is the determination, for a prescribed A, of a complement B that is in some sense minimal. Erdös [1] and Lorentz [2] have discussed some problems and concepts for the case where A is an infinite set; D. J. Newman [3] has dealt with finite sets A. We have also obtained some results for the case where A is finite, and they will appear elsewhere [5]. Here we generalize this concept in several respects.

Let G be a group on which a measure m is defined. If A, B ⊂ G we define A ⊕ B = \{c|c = a + b, a ∈ A, b ∈ B\}. By A_k ⊂ G we denote a subset of G consisting of k elements. Given nonempty A we can find B such that A ⊕ B = G. We then say that A and B are complementary and render the situation asymmetrical by thinking of A as a set of translates and B as a set which is to be translated so that the union of its translates covers G.

Given A_k one may ask for the set B such that A_k ⊕ B = G and m(B) is a minimum. More precisely, we define s(A_k) = \inf\{m|B ⊂ G, A_k ⊕ B = G\}. It is then natural to seek s(A_k) for the “worst” A_k, i.e. s(A_k) corresponding to the set of shifts which necessitates the “biggest” complementary set. We so define c_k = \sup_{A_k ⊂ G} s(A_k). Theorems 1, 2, and 3 deal with the problem of determining c_k.

In the dual problem we are given B, m(B) > 0, and asked to find minimal A such that A ⊕ B = G or, sometimes, m(A ⊕ B) = m(G). As before, we seek
the “worst” $B$, i.e., the $B$ of given measure which necessitates the “largest” $A$.

The results obtained in connection with this problem are somewhat surprising. If the question asked by Erdős could be answered in the affirmative they would be even more surprising. Theorems 5 and 6 deal with the dual problem.

**Definition.** $C_k = \sup_G \max_{A_k} \min_B d(B)$, where $G$ is a finite group containing at least $k$ elements, $A_k$ is a $k$ element subset of $G$, and $B$ is a complement of $A_k$ in $G$, i.e., $A_k \oplus B = G$.

**Theorem 1.** $C_k \leq (\log k + 2)/k$.

**Proof.** The proof that D. J. Newman [3] gives to show $c_k \leq (1 + \log k)/k$ is applicable here with slight change.

Let $G$ be a group of $N$ elements, $N > k$, and $A_k \subseteq G$, where $A_k = \{0 = a_1, \ldots, a_k\}$. For each element $a_n \in G$ we denote by $U_n$ the set of elements $-a_1 + a_n, -a_2 + a_n, \ldots, -a_k + a_n$. $U$ represents an unspecified class $U_n$ and $T$ denotes an unspecified set of $K$ elements. Clearly, there are $\binom{N}{K}$ sets $T$, and for each $n$, exactly $\binom{N-k}{K}$ of these sets do not meet the set $U_n$. Since there are at most $N$ different sets $U_n$, it follows that there are at most $N\binom{N-k}{K}$ disjoint pairs $T, U$. Consequently, at least one of the sets $T$ misses at most

\[ N\left(\binom{N-k}{K}\right)/\binom{N}{K} \]

of the sets $U_n$. Let $S$ consist of such a set $T$, together with all elements $a_n$ for which $T \cap U_n = \emptyset$.

To see that $S$ is a complement of $A$, let $a_m \in G$. If $T \cap U_m = \emptyset$, we have the representation $a_m = 0 + a_m \ (0 \in A, a_m \in S)$.

If $T \cap U_m$ contains some element $-a_i + a_m$, we have the representation $a_m = a_i + (-a_i + a_m), (a_i \in A, -a_i + a_m \in S)$.

We now choose $K$ such that $N(\log k/k) < K < N(\log k/k) + 1$ and proceed to obtain an upper bound for the density of $S$:

\[ d(S) \leq d(T) + N\left(\binom{N-k}{K}\right)/\binom{N}{K} \cdot \frac{1}{N} = \frac{K}{N} + \left(\binom{N-k}{K}\right)/\binom{N}{K} \]

\[ \leq \frac{K}{N} + \left(1 - \frac{k}{N}\right)^K \leq \frac{K}{N} + e^{-kN/k} \]

\[ \leq \frac{N(\log k/k) + 1}{N} + e^{-(k/N)(N\log k/k)} = \frac{\log k}{k} + \frac{1}{N} \]

\[ \leq \frac{\log k + 2}{k}. \]
This proves the assertion.

**Theorem 2.** Let $T^2$ be the 2-dimensional torus whose points are 2-tuples $(x_1, x_2)$ and where addition of points is modulo 1. Let $A_k = \{a_1, a_2, \ldots, a_k\}$ be an arbitrary set of $k$ distinct points in $T^2$. Then we can find a set $B \subset T^2$ such that $A_k \oplus B = T^2$ and $m(B) \leq K_2((\log k + 2)/k)$, where $K_2$ is a constant.

**Proof.** Let $L_n$ consist of all points $r_i = (p_i/n, q_i/n)$, where $p_i, q_i$ are integers, $0 \leq p_i < n$, $0 \leq q_i < n$. Clearly $L_n$ is a finite subgroup of $T^2$. Moreover, we may think of $L_n$ as partitioning $T^2$ into little squares, $S_i$, $i = 1, \ldots, n^2$, of side $1/n$. We assign to each square the index $i$ assumed by the point of its lower left-hand corner $r_i$.

Now for each point $a_j \in A_k$ there is at least one closest point in $L_n$. Let $r_{i_j}$ be such a point. This process must result in the assignment of $k$ different points of $L_n$ if $n$ is sufficiently large. If we define $A'_k = \{r_{i_1}, r_{i_2}, \ldots, r_{i_k}\}$, the set of grid points closest to $A_k$, then by Theorem 1 we can find $B'$, another subset of $L_n$, where $A'_k \oplus B' = L_n$ and $|B'| \leq ((\log k + 2)/k)n^2$. If we now define $B$ as the set of squares whose lower left-hand points are the elements of $B'$, then clearly $A'_k \oplus B = T^2$ and $m(B) \leq (\log k + 2)/k$.

If $a_j \in A_k$, $r_{i_j}$ is its closest point in $L_n$, and $S_m$ is an arbitrary square in $B$, then $r_{i_j} \oplus S_m$ exactly covers some other square $S'_m$, but $a_j \oplus S_m$, while intersecting $S'_m$, will not completely cover it. Hence, $S_m$ must be enlarged if we wish $S'_m \subset a_j \oplus S_m$ and it is certainly sufficient to double the length of each side of $S_m$ while preserving its center. If we perform this operation for every square in $B$ and call the set of enlarged squares $B$, then $A_k \oplus B = T^2$ and $m(B) \leq 4((\log k + 2)/k)$. This proves the assertion.

**Corollary.** If $T^n$ is the $n$-dimensional torus and $A_k$ is an arbitrary set of $k$ points in $T^n$, then we can find a set $B \subset T^n$ such that $A_k \oplus B = T^n$ and $m(B) \leq K_n(\log k/k)$, where $K_n \leq 2^n$.

**Proof.** Essentially the same as above.

**Note.** If the points in $A_k$ are all rational then they are all elements of $L_n$ for some $n$. Hence, no enlargement is necessary and we may take $K_n = 1$.

**Theorem 3.** Let $G$ be a compact, completely separable topological group and $\varepsilon > 0$. Then there exists $B \subset G$ with $m(B) < \varepsilon$ such that for all $A \subset G$ with $(\overline{A})^0 \neq \emptyset$ we have $A \cdot B = B \cdot A = G$.

**Proof.** Let $Z = \{z_1, z_2, \ldots\}$ be a dense denumerable subset of $G$ and $Z^{-1} = \{z_1^{-1}, z_2^{-1}, \ldots\}$ the set of its inverses. Let $T_i$ be an open set such that $z_i^{-1} \in T_i$ and $m(T_i) < \varepsilon/2^{i+1}$ and let $S_i$ be an open set such that $z_i \in S_i$, $S_i^{-1} \subset T_i$, and $m(S_i) < \varepsilon/2^{i+1}$, for $i = 1, 2, \ldots$. Define
Clearly $m(S) < e/2$, $m(T) < e/2$, and $S^{-1} \subset T$.

We first show $xA \cap S \neq \emptyset$ for all $x \in G$. Clearly $x(A)^0 \cap Z \neq \emptyset$. So, for
some $i$, $z_i \in x(A)^0 \cap Z$. Since $z_i$ is a limit point of $xA$, $S_i$ must contain a point
of $xA$; hence $xA \cap S \neq \emptyset$. The same argument shows that $Ax \cap S \neq \emptyset$ for all
$x \in G$.

Now let $B = S \cup T$. We have $xA \cap S \neq \emptyset$, $x \in G \Rightarrow A \cap xS \neq \emptyset$, $x \in G,$
$\Rightarrow xs = a \Rightarrow x = as^{-1}$ has a solution for every $x$, with $a \in A$, $s^{-1} \in T \subset B$. Hence
$A \cdot B = G$.

Similarly, $Ax \cap S \neq \emptyset$, $x \in G \Rightarrow A \cap Sx \neq \emptyset$, $x \in G$, $\Rightarrow sx = a \Rightarrow x =s^{-1}a$ has a solution for every $x$, with $s^{-1} \in T \subset B$, $a \in A$. Hence $B \cdot A = G$.

Since $m(B) < e$ this proves the theorem.

**Definition.** $\Delta^B_x = B \cup B_x - B \cap B_x$ where $B_x = x \oplus B \pmod{1}$.

**Theorem 4.** Let $B \subset [0, 1)$ and $m(B) = e > 0$. Then, if $m(\Delta^B_x) = 0$ for
all $x \in [0, 1)$, $e = 1$.

**Proof.** We first note that $m(B \cup B_x) \geq e$ and $m(B \cap B_x) \leq e$ so that
$m(\Delta^B_x) = 0$ implies $m(B \cup B_x) = e$.

Suppose there exists an interval $(\alpha, \beta)$ such that $m(B \cap (\alpha, \beta)) = 0$. Then
we can find $x$ such that $m(B_x \cap (\alpha, \beta)) > 0$. This implies $m(B \cup B_x) > e$ which
implies $m(\Delta^B_x) > 0$. The contradiction shows that for every interval $(\alpha, \beta)$ we
have $m(B \cap (\alpha, \beta)) > 0$.

Suppose $E \subset [0, 1)$ is such that $m(B \cap E) = \delta$. If there exists $x$ such that
$m(B_x \cap E) \neq \delta$ then again this implies $m(B \cup B_x) > e$. Hence if $m(B \cap E) = \delta$
then $m(B_x \cap E) = \delta$ for all $x \in [0, 1)$.

So if $\beta - \alpha > 1/n$, $m(B \cap (\alpha, \beta)) = e \cdot 1/n$ because we can partition $[0, 1)$
into $n$ nonoverlapping intervals of length $1/n$. Similarly, if $\beta - \alpha = 1/(n + \theta)$,
$0 < \theta < 1$, then $m(B \cap (\alpha, \beta)) > \frac{1}{2}e/(n + \theta)$. Hence, by a result of Titchmarsh
$m(B) = 1$.

**Note.** In all that follows addition is mod 1.

**Theorem 5(A).** For every $\varepsilon > 0$ there exists $B \subset [0, 1)$ such that $m(B) \geq
1 - \varepsilon$ and $m(A \oplus B) = 1$ implies $A$ is infinite.

**Theorem 5(B).** For every $B \subset [0, 1)$, $m(B) > 0$, we can find $A$ such that
$m(A \oplus B) = 1$ and $A$ is denumerable.

**Proof of (A).** Suppose $B \subset [0, 1)$ is nowhere dense and $m(B) = 1$. Then
$m(B) = 1$ implies $(B)'$ is open and $m(B') = 0$. Only $\emptyset$ is open and has measure
zero so $B = [0, 1)$ and the contradiction shows there does not exist a nowhere
dense set, in $[0, 1)$, of measure 1.
It is well known that the class of all nowhere dense subsets of a metric space is a finitely additive class.

By changing the lengths of the extracted intervals in the construction of the Cantor ternary set, we can construct a perfect nowhere dense set $B$ in $[0, 1)$, which has measure greater than $1 - \varepsilon$ for any $\varepsilon > 0$.

Hence, if $A$ is any finite point set in $[0, 1)$ then $C = A \oplus B$ is nowhere dense and therefore $m(C) < 1$.

**Proof of (B).** Denote by $\bigcup B_{x_i}$ the set $\bigcup_{i=1}^{\infty} x_i + B$, where $\{x_i\}$ is an infinite sequence in $[0, 1)$.

Let $\alpha = \sup m(\bigcup B_{x_i})$ where the sup is over all such sequences. Then, for every $n$ we can find a sequence $\{x_i^{(n)}\}$ such that $m(\bigcup B_{x_i^{(n)}}) > \alpha - 1/n$. Clearly, $m(\bigcup_{B_{x_i^{(n)}}}) = \alpha$ so that the sup is actually attained for some denumerable sequence $\{x_i^{(0)}\}$. Now we write $\beta = \bigcup B_{x_i^{(0)}}$ and note that we have just proved $m(\Delta_{x_i^{(0)}}) = 0$ for all $x \in [0, 1)$ and so, by Theorem 4, we have $\alpha = m(\beta) = 1$. If we let $A = \bigcup x_i^{(0)}$ then $m(A \oplus B) = 1$ and $A$ is denumerable.

**Note.** All sets are subsets of $I = [0, 1)$.

**Theorem 6.** (A) There exists $B \in \mathcal{C}at. II, m(B) = 1$ such that $A \oplus B = I$ implies $A$ is infinite.

(B) On the other hand, for every $B$, $m(B) > 0$, we can find $A$ such that $A \oplus B = I$ and $m(A) = 0$.

**Proof of (A).** Every $x \in [0, 1)$ can be written $x = \Sigma_{k=0}^{\infty} a_k/n^k$, $0 < a_k < n$, $n > 2$. Let $X_n$ be the class of numbers $x = \Sigma_{k=1}^{\infty} a_k/n^k$, $0 < a_k < n - 1$, $n \geq 2$. Clearly $m(X_n) = 0$. Define $B' = \bigcup_{n=2}^{\infty} X_n$. From this it follows that $m(B) = 1$. Since $X_n$ is perfect and nowhere dense, $B' \in \mathcal{C}at. I$ and hence $B$ is a residual set.

Suppose $B$ and any 2 shifts of $B$ fail to cover $I$. Then for any pair $x_1, x_2 \in I$ we can find $d_1, d_2, d_3 \in B'$ such that

$$x_1 + d_1 = d_3, \quad x_2 + d_2 = d_3.$$

It is also clear that this condition is sufficient to guarantee that $B$ and any 2 shifts of $B$ fail to cover $I$.

We can generalize this by stating the following: a necessary and sufficient condition that $B$ and any $m$ shifts of $B$ fail to cover $I$ is that for any $m$ elements of $I$: $x_1, \ldots, x_m$, there exist $m + 1$ elements in $B'$: $d_1, \ldots, d_{m+1}$, such that

$$x_1 + d_1 = d_{m+1}, \quad x_2 + d_2 = d_{m+1}, \ldots, \quad x_m + d_m = d_{m+1}.$$

In fact we can already find these $m + 1$ elements: $d_1, \ldots, d_{m+1}$, in $X_n$ if only $n > m + 1$. 

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If we denote by \( x_{j,1}x_{j,2} \cdots x_{j,k} \cdots \) the number
\[
x_j = \sum_{q=1}^{\infty} x_{j,q}/n^q,
\]
and denote by \( d_{k,1}d_{k,2} \cdots d_{k,r} \cdots \) the number
\[
d_k = \sum_{q=1}^{\infty} d_{k,q}/n^q,
\]
then the above claim is equivalent to stating that the congruences:
\[
\begin{align*}
x_{1,i} + d_{1,i} + p_{1,i} \equiv d_{m+1,i} & \pmod{n} \\
x_{2,i} + d_{2,i} + p_{2,i} \equiv d_{m+1,i} & \pmod{n} \\
\vdots \\
x_{m,i} + d_{m,i} + p_{m,i} \equiv d_{m+1,i} & \pmod{n}
\end{align*}
\]
are solvable subject to the constraints \( 0 < d_{k,i} < n - 1, \ 1 \leq k \leq m + 1, \ i = 1, 2, \cdots \).

Recall that \( 0 < x_{k,i} < n \). Now \( p_{j,i} = 1 \) if \( x_{j,i+1} + d_{j,i+1} + p_{j,i+1} \geq n \); \( p_{j,i} = 0 \) otherwise.

Assume that \( p_{j,i}, \ j = 1, \ldots, m, \) have been determined. Then for \( x_{1,i} \) there are at least \( n - 2 \) possible values for \( d_{m+1,i} \). Only the values of \( d_{m+1,i} \) such that \( x_{1,i} + (n - 1) + p_{1,i} \equiv d_{m+1,i} \pmod{n} \) and \( d_{m+1,i} = (n - 1) \) are inadmissible. Of these \( n - 2 \) possible values exactly \( n - 3 \) are still possible solutions for \( x_{2,i} \) and so, by the time we reach \( x_{m,i} \), there are still \( n - m - 1 \) possible values for \( d_{m+1,i} \). Since we assumed \( n > m + 1 \) the assertion is proved.

We have shown that no finite set of shifts of \( B \) covers \( I \). Since \( B \) is a residual set, and therefore of Cat. II, the theorem is proved.

**Proof of (B).** By Theorem 5(B) we can find \( F \) such that \( m(F \oplus B) = 1 \) and \( F \) is denumerable. We can also add one element to \( F \), if necessary, so that \( 0 \in C = F \oplus B \). Then \( m(C') = 0 \) and we define \( \bar{C} = C' \cup \{0\} \). Then \( I = \bar{C} \oplus C = \bar{C} \oplus F \oplus B = A \oplus B \) if we define \( A = \bar{C} \oplus F \). Since \( F \) is denumerable and \( m(A) = 0 \) we have \( m(A) = 0 \).

**Note.** P. Erdös asks [4] whether, in Theorem 6(A), infinite can be changed to nondenumerable.

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