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On a theorem of Hildebrand

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We give a short proof that for each multiplicative subgroup H of finite index in $\mathbb{Q}^+$, the set of integers a with $a, a+1 \in H$ is an IP-set. This generalizes a theorem of Hildebrand concerning completely multiplicative functions taking values in the k-th roots of unity.

A theorem of Hildebrand [1991, Theorem 2], which was essential in answering a question of Lehmer, Lehmer and Mills [Lehmer et al. 1963] on consecutive power residues can be formulated as follows:

Theorem 1 (Hildebrand). *Fix some $k \in \mathbb{Z}^+$. If $f : \mathbb{Z}^+ \to \mathbb{C}$ is a completely multiplicative function (i.e., $f(mn) = f(m)f(n)$ for all $m, n \in \mathbb{Z}^+$) taking its values in the k-th roots of unity then the set of $a \in \mathbb{Z}^+$ fulfilling $f(a) = f(a+1) = 1$ is nonempty.*

Remark 2. Hildebrand actually proved more; i.e., there is a constant $c(k)$, independent of the specific multiplicative function f, and an $a \in \mathbb{Z}^+$ such that $a \leq c(k)$ and $f(a) = f(a+1) = 1$. By a standard compactness argument, these versions can be seen to be equivalent. It should, however, be noted that from Hildebrand's proof one can get an effective value for $c(k)$ (as was pointed out by the anonymous referee).

It makes sense to restate Hildebrand's result as follows:

Theorem 3 (Hildebrand). *Let $H \leq \mathbb{Q}^+$ be a (multiplicative) subgroup such that $\mathbb{Q}^+/H$ is cyclic of finite order. Let $H^* := H \cap \mathbb{Z}^+$. Then $H^* \cap (H^* - 1)$ is nonempty.*

The original proof made use of analytic methods and was rather long. We will give a short elementary proof of a more general theorem.

However, before we can state (and prove) our generalization we need some notation and the set-theoretical version of Hindman's theorem:

We denote by $\mathcal{P}^{\text{fin}}(\mathbb{Z}^+)$ the set of finite, nonempty subsets of $\mathbb{Z}^+$.

For $A, B \in \mathcal{P}^{\text{fin}}(\mathbb{Z}^+)$ write $A \prec B$ if $\max A < \min B$.

Furthermore, for a sequence $A_1 \prec A_2 \prec \cdots$ in $\mathcal{P}^{\text{fin}}(\mathbb{Z}^+)$, we define

$$\text{FU}((A_i)_{i \in \mathbb{Z}^+}) = \left\{ \bigcup_{i \in I} A_i : I \subseteq \mathbb{Z}^+,\ 0 < |I| < \infty \right\}.$$

Similarly, for a sequence $a_1, a_2, \ldots$ in $\mathbb{Z}^+$, we define

$$\text{FS}((a_i)_{i \in \mathbb{Z}^+}) = \left\{ \sum_{i \in I} a_i : I \subseteq \mathbb{Z}^+,\ 0 < |I| < \infty \right\}.$$

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We call a set $M \subseteq \mathbb{Z}^+$ an *IP-set* [Hindman and Strauss 2012, Definition 16.3] if there is a sequence $a_1, a_2, \dots$ in $\mathbb{Z}^+$ such that $\mathrm{FS}((a_i)_{i \in \mathbb{Z}^+}) \subseteq M$.

If a set A is the disjoint union of subsets $B_1, \dots, B_n \subseteq A$, that is, $B_1 \cup \dots \cup B_n = A$ and $B_i \cap B_j = \varnothing$ for $1 \le i < j \le n$, we denote this relation by $A = B_1 \sqcup \dots \sqcup B_n$.

Now Hindman's theorem on partitions of $\mathcal{P}^{\mathrm{fin}}(\mathbb{Z}^+)$ [Hindman and Strauss 2012, Corollary 5.17] can be stated as follows:

Theorem 4 (Hindman). *For any finite partition $\mathcal{P}^{\mathrm{fin}}(\mathbb{Z}^+) = M_1 \sqcup M_2 \sqcup \dots \sqcup M_n$ there are sets $A_1 \prec A_2 \prec \cdots$ and $1 \le j \le k$ such that*

$$\mathrm{FU}((A_i)_{i \in \mathbb{Z}^+}) \subseteq M_j.$$

We can now state our generalization of Hildebrand's theorem:

Theorem 5. *Let $H \le \mathbb{Q}^+$ be a (multiplicative) subgroup of finite index.*[1] *Let $H^* := H \cap \mathbb{Z}^+$. Then $H^* \cap (H^* - 1)$ is an IP-set.*

Hildebrand's proof of Theorem 3 is an application of Ramsey's theorem on *special* sets, i.e., finite sets $\{n_1 < n_2 < \dots < n_r\}$ such that $n_j - n_i = \gcd(n_i, n_j)$ holds for $1 \le i < j \le r$.

We will use a similar concept:

Definition 6. For a sequence s_n and a finite subset $A \subset \mathbb{Z}^+$, set

$$s_A := \sum_{n \in A} s_n.$$

A *block-divisible sequence* is a strictly decreasing sequence s_n in $\mathbb{Z}^+$ such that for $A, B \in \mathcal{P}^{\mathrm{fin}}(\mathbb{Z}^+)$, s_A divides s_B whenever $A \prec B$.

For our proof, *any* block-divisible sequence will work. Thus, we only need to confirm the existence of block-divisible sequences:

Lemma 7. *There is a block-divisible sequence in $\mathbb{Z}^+$.*

Proof. We construct a sequence as follows:

$$s_0 := 1, \quad s_{n+1} := \prod_{\substack{A \subseteq \{0, \dots, n\} \\ A \neq \varnothing}} s_A.$$

Ignoring the s_0 at the beginning, we end up with a strictly increasing sequence fulfilling the desired divisibility condition. □

Now we can show our main result:

Proof of Theorem 5. Let N_i' $(1 \le i \le k)$ be the (multiplicative) cosets of H in $\mathbb{Q}^+$.

These give a finite partition $\mathbb{Z}^+ = N_1 \sqcup N_2 \sqcup \dots \sqcup N_k$, where $N_i = N_i' \cap \mathbb{Z}^+$.

We now fix a block-divisible sequence s_n (whose existence is guaranteed by Lemma 7) and define a partition $\mathcal{P}^{\mathrm{fin}}(\mathbb{Z}^+) = M_1 \sqcup M_2 \sqcup \dots \sqcup M_k$ by declaring $A \in M_i$ if and only if $s_A \in N_i$.

By Theorem 4 there is a sequence $A_1 \prec A_2 \prec \cdots$ such that $\mathrm{FU}(A_1, A_2, \dots)$ is contained in one M_i for some $1 \le i \le k$.

[1] Note that we do not require $\mathbb{Q}^+/H$ to be cyclic.

By the definition of block-divisibility, s_{A_1} divides s_A for all $A \in \mathrm{FU}(A_2, A_3, \dots)$ and, consequently, for all $A \in \mathrm{FU}(A_1, A_2, \dots)$, too.

Thus, defining $b_i := s_{A_i}$, the members of $\mathrm{FS}(b_1, b_2, \dots)$ all lie in the same coset of H and are divisible by b_1. Therefore, setting $a_i := b_i/b_1$, one has

$$\mathrm{FS}(a_1, a_2, \dots) = \mathrm{FS}(1, a_2, a_3, \dots) \subseteq H^*.$$

Furthermore, $\mathrm{FS}(1, a_2, a_3, \dots) = \mathrm{FS}(a_2, a_3, \dots) \cup (\mathrm{FS}(a_2, a_3, \dots) + 1) \subseteq H^*$.

We conclude that $\mathrm{FS}(a_2, a_3, \dots) \subseteq H^* \cap (H^* - 1)$. □

Remark 8. We use the terminology of Theorem 5 to summarize the state of possible generalizations:

There are (multiplicative) subgroups H of arbitrary even index in $\mathbb{Q}^+$ such that $H^* \cap (H^* - 1) \cap (H^* - 2)$ is empty, as has been shown by Lehmer and Lehmer [1962, p. 103].

Graham [1964] proved that there are subgroups of arbitrary (finite) index in $\mathbb{Q}^+$ such that $H^* \cap \cdots \cap (H^* - 3)$ is empty.

However, if $\mathbb{Q}^+/H$ is of odd order k, it is still an open question if $H^* \cap (H^* - 1) \cap (H^* - 2)$ is necessarily nonempty. Only in the case $k = 3$ is this set known to be always nonempty, as has been shown computationally by Lehmer, Lehmer, Mills and Selfridge [Lehmer et al. 1962]. Maybe the combinatorial methods presented in this article may help in resolving this problem!

Remark 9. Some ideas shown in this article are based on notes of the author, [Dietzel 2013], which have not been submitted to any journal.

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