A CONSTRUCTION FOR PARTITIONS WHICH AVOID LONG ARITHMETIC PROGRESSIONS

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For $k \geq 2$, $t \geq 2$, let $W(k, t)$ denote the least integer m such that in every partition of m consecutive integers into k sets, at least one set contains an arithmetic progression of $t+1$ terms. This paper presents a construction which improves the best previously known lower bounds on $W(k, t)$ for small k and large t.

1. Introduction. For $k \geq 2$, $t \geq 2$, let $W(k, t)$ denote the least integer m such that in every partition of m consecutive into k sets, at least one set contains an arithmetic progression of $t+1$ terms. According to a well-known theorem of van der Waerden (1925), $W(k, t) < \infty$. It is obvious that

$$W(k, t) \leq W(k, t+1) \quad . \tag{1}$$

Using random coding arguments, Erdös and Radó (1952) have shown that

$$W(k, t) \geq [2t k^t]^{1/2} \quad . \tag{2}$$

By a more refined nonconstructive argument, Schmidt (1962) has shown that

$$W(k, t) \geq k^{(t+1) - c[(t+1)\log(t+1)]^{1/2}} \tag{3}$$

where c is an absolute constant. The major result of this paper is

THEOREM 1. _If_ k _is a prime-power, and if_ $\check{W}$ _is an integer such that_

$$\check{W} \leq t(k^t - 1)/k^d - 1) \quad . \tag{4}$$

for all d _which are proper divisors of_ t, _and if_

$$\check{W} \leq t(k^t - 1)/D \tag{5}$$

for all $D < t$ _which are divisors of_ $k^t - 1$, _then_

$$W(k, t) > \check{W} \tag{6}$$

The proof consists of a construction, based on the Galois field $GF(k^t)$, which partitions $\check{W}$ consecutive integers into k sets, none of which contains any arithmetic progression longer than t. In some cases this construction can be extended by special arguments, to give

THEOREM 2. If t is prime, $W(2, t) > t2^t$.

The bound of Theorem 2 is stronger than equation (3). If t is the square of a prime or the product of two large primes whose difference is small, then Theorem 1 again represents a slight improvement over equation (3). However, for most values of t, the bound of Theorem 1 can be improved by decreasing t to the next smaller prime and invoking equation (1). Although this technique gives the best known bound for small k and large t, the construction of L. Moser (1960) still gives the best known bound for small t and large k, namely,

$$W(k, t) > tk^{c \log k} . \tag{7}$$

The bound of Theorem 2 is also disappointing for small values of t. Theorem 2 shows only that $W(2, 3) > 24$, yet J. Folkman (1967) has shown that $W(2, 3) > 34$ by the following construction: For $i = 0, 1, 2, \ldots, 33$, let $i \in S_0$ if $i = 0, 11$, or a quadratic nonresidue mod 11. It is believed that Folkman's partition is the best possible, and that $W(2, 3) = 35$. Similar constructions using quadratic residues modulo certain larger primes may be used to obtain other lower bounds on $W(2, t)$, but the general form of these bounds is unknown for large values of t.

2. Proof of Theorem 1. Let α be a primitive element in $GF(k^t)$. Then every nonzero element in $GF(k^t)$ is a power of α, and $\alpha^i = \alpha^j$ if and only if $i \equiv j \bmod k^t - 1$. Let $\beta_1, \beta_2, \ldots, \beta_t$ be a set of elements in $GF(k^t)$ which are linearly independent over $GF(k)$. Since these elements form a basis of $GF(k^t)$ over $GF(k)$, there exist elements $A_{i,j} \in GF(k)$ such that

$$\alpha^j = \sum_{i=1}^{t} A_{i,j} \beta_i .$$

The field element α^j is the root of some irreducible monic polynomial, $f^{(j)}(x) = \sum_{n=0}^{t} f_n^{(j)} x^n$, where $f_n^{(j)} \in GF(k)$. The degree of $f^{(j)}(x)$ is a divisor of t.

For each $\xi \in GF(k)$, we define the set of integers S_ξ by the rule

$$i \in S_\xi \text{ if and only if } 0 \le i < \check{W} \text{ and } A_{1,i} = \xi .$$

Similarly, for each $\xi \in GF(k)$, we define the set of nonzero field elements, T_ξ, by the rule $\alpha^i \in T_\xi$ for each $i \in S_\xi$.

We now claim that no S_ξ contains any arithmetic progression of length $> t$. Let us suppose that for some $b \neq 0$,

$$\{a, a+b, a+2b, \ldots, a+tb\} \subset S_\xi \quad . \tag{8}$$

Since $0 \le a < a+tb < \check{W}$, we have

$$b < (k^t - 1)/(k^d - 1) \tag{9}$$

and

$$b < (k^t - 1)/D \tag{10}$$

from equations (4) and (5). We now consider separately the cases $\xi \neq 0$ and $\xi = 0$.

Case 1: $\xi \neq 0$. Since $\alpha^a f^{(b)}(\alpha^b) = 0$, we have $0 = \sum_{n=0}^{t} f_n^{(b)} \alpha^{a+bn} = \sum_{n=0}^{t} f_n^{(b)} \sum_{j=1}^{t} A_{j,a+bn} \beta_j$. Since $\beta_1, \beta_2, \ldots, \beta_t$ are linearly independent, this implies that for every j,

$$\sum_{n=0}^{t} f_n^{(b)} A_{j,a+bn} = 0 \quad . \tag{11}$$

In particular, since $A_{1,a+bn} = \xi$ for $n = 0, 1, \ldots, t$, we may set $j = 1$ in equation (11) and obtain $\xi \sum_{n=0}^{t} f_n^{(b)} = 0$. If $\xi \neq 0$, this implies that $0 = \sum_{n=0}^{t} f_n^{(b)} = f^{(b)}(1)$. Therefore, $f^{(b)}(x)$ is divisible by $x-1$. Since $f^{(b)}(x)$ is irreducible, $f^{(b)}(x) = x-1$, $\alpha^b = 1$, and $b \equiv 0 \bmod k^t - 1$, contradicting both equations (9) and (10).

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Case 2: $\xi = 0$. A weakened form of equation (8) is

$$\{a+b, a+2b, \ldots, a+tb\} \subset S_0 . \tag{12}$$

By definition of T_0, equation (12) implies that T_0 contains the elements $\alpha^{a+b}, \alpha^{a+2b}, \ldots, \alpha^{a+tb}$. We claim that these t elements are distinct, for if $\alpha^{a+nb} = \alpha^{a+mb}$, then $(n-m)b \equiv 0 \bmod k^t-1$, contradicting equation (10). Since T_0 is a subspace of dimension $t-1$ over $GF(k)$, any t distinct elements in T_0 must be linearly dependent. Therefore, there exist $B_1, B_2, \ldots, B_t \in GF(k)$ such that $\sum_{n=1}^{t} B_n \alpha^{a+bn} = 0$. This implies that α^b is a root of the polynomial $\sum_{n=1}^{t} B_n x^{n-1}$. Since the degree of this polynomial is less than t, $\alpha^b \in GF(k^d)$, where d is a proper divisor of t. Thus, $(\alpha^b)^{(k^d-1)} = 1$, so $b(k^d-1) \equiv 0 \bmod k^t-1$, contradicting equation (9). We conclude that equation (12) is possible only if b is larger than the bounds of equation (9) or equation (10).

Proof of Theorem 2. If p and t are odd primes, then Fermat's theorem shows that $2^{(p-1)} \equiv 1 \bmod p$ so $2^t \not\equiv 1 \bmod p$ unless $p \equiv 1 \bmod t$. In other words, if D is any divisor of 2^t-1, then $D \geq t+1$, so Theorem 1 asserts that $W(2,t) > \check{W}$, where $\check{W} = t(2^t-1)$. We shall now show that the construction of Theorem 1 can be extended to include t additional consecutive integers.

The construction of Theorem 1 is valid for any choice of β's, so we may now choose these basis elements as follows:

$$\beta_1 = 1, \ \beta_2 = 1+\alpha, \ldots, \beta_{(t+1)/2} = 1+\alpha^{(t-1)/2}; \tag{13}$$

$$\beta_{(t+3)/2} = 1+\alpha^{-1}, \beta_{(t+5)/2} = 1+\alpha^{-2}, \ldots, \beta_t = 1+\alpha^{-(t-1)/2} .$$

If these β's were linearly dependent, then α would be a root of a polynomial of degree $\leq t-1$, contradicting the assumption that α is a primitive element in $GF(2^t)$.

With the basis chosen by equation (13), the proof of Theorem 1 partitions $\{0, 1, 2, \ldots, \check{W}-1\}$ into disjoint sets S_0 and S_1, with the property that

(14) $$\{0, 1, 2, \ldots, (t-1)/2\} \subset S_1 .$$

and

(15) $$\{\check{W}-1, \check{W}-2, \ldots, \check{W}-(t-1)/2\} \subset S_1 .$$

We set $S_0^+ = S_0 \cup S_0' \cup S_0''$ where

$$S_0' = \{-1, -2, \ldots, -(t-1)/2\}$$

$$S_0'' = \{\check{W}, \check{W}+1, \ldots, \check{W}+(t-1)/2\} .$$

Any arithmetic progression of length $t+1$ in S_0^+ would have to be of one of the following types:

1) Including an element in S_0' and another element in S_0''. This is impossible because the difference between any two such numbers is not divisible by t.

2) Including two or more elements in S_0' [or S_0'']. This is blocked by equation (14) (or equation (15)).

3) Including one element in S_0' (or S_0'') and an arithmetic progression of length t is S_0. According to the proof of Theorem 1, the only arithmetic progressions of length t in S_0' are those in which $b \geq 2^t - 1$. The total span of the extension of such a progression would be $\geq t(2^t-1)$, contradicting equation (15) (or equation (14)).

Therefore, S_0^+ and S_1 partition the integers from $-(t-1)/2$ to $\check{W} + (t-1)/2$ into two sets, neither of which contains any arithmetic progression longer than t. This partition can be translated to a partition of the integers from 0 to $t2^t - 1$ (or from 1 to $t2^t$) by adding $(t-1)/2$ (or $(t+1)/2$) to each element in S_0^+ and S_1.

The construction of Theorem 1 may also be extended slightly for other values of t and k, but the improvement is always relatively small.

3. <u>Example.</u> Let $k = 2$, $t = 3$, $\check{W} = 21$. Take α as a root of x^3+x+1; $\beta_1 = 1$, $\beta_2 = 1+\alpha = \alpha^3$; $\beta_3 = 1+\alpha^{-1} = \alpha^2$. For $i = 1, 2, 3$; $j = 0, 1, 2, \ldots, 20$, $A_{i,j}$ is given by

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01011100101110010111 0
00101110010111001011 1

so $S_1 = \{0, 1, 4, 6, 7, 8, 11, 13, 14, 15, 18, 20\}$; $S_0 = \{2, 3, 5, 9, 10, 12, 16, 17, 19\}$; $S_0^+ = S_0 \cup \{-1, 21, 22\}$.

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